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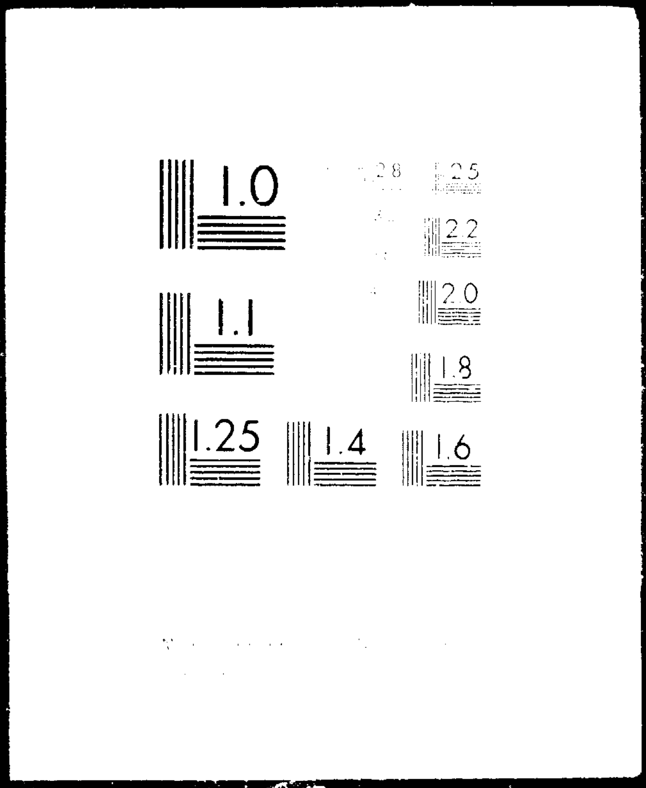

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GENERAL AVIATION TURBINE ENGINE (GATE) STUDY FINAL REPORT

BY E.J. LAYS AND D.L. MURRAY

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2280 WEST MAPLE ROAD
WALLED LAKE, MICHIGAN 48088

PREPARED FOR

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA LEWIS RESEARCH CENTER
CLEVELAND, OHIO 44135

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16. Abstract

Because of acknowledged safety and utility benefits, there is substantial general aviation manufacturer and user interest in turbine powerplants. Yet, only five percent of the general aviation fleet is turbine powered and there are virtually no production turbine-powered fixed wing airplanes under 2722 kg (6000 lbm). The problem is powerplant cost and fuel efficiency. The General Aviation Turbine Engine (GATE) program was conceived to explore solutions to this problem. Concepts are discussed that project engine cost savings through use of geometrically constrained components designed for low rotational speeds and low stress to permit manufacturing economies. Aerodynamic development of geometrically constrained components is recommended to maximize component efficiency. Conceptual engines, airplane applications, airplane performance, engine cost, and engine-related life cycle costs are presented. The powerplants proposed in this report offer encouragement with respect to fuel efficiency and life cycle costs and make possible remarkable airplane performance gains.

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FOREWORD

This report documents results of a study of advanced general aviation turbine engine (GATE) concepts accomplished for the National Aeronautics and Space Administration (NASA), Lewis Research Center, under the direction of Mr. William C. Strack, NASA Project Manager. It was prepared in accordance with requirements in Section 5.2, Exhibit A, Statement of Work, of Contract NAS3-20758 and is one of four reports prepared by GATE contractors. Details concerning the other reports can be obtained from Mr. Strack.

For turbine engines to be viable alternatives to piston engines for general aviation applications, certain economic and performance tests must be passed. The piston engine dominance of the general aviation market provides ample evidence that these tests are not being passed by contemporary turbine engine candidates. It was therefore fitting, with respect to work under this contract, that proposed turbine powerplants be measured against piston counterparts for installed fuel efficiency and life cycle cost. Although the present work has to be considered first cut, it could not have been performed with dispatch without the cooperation of airframe manufacturers. The authors, therefore, wish to express their appreciation to Piper Aircraft Corporation, Mooney Aircraft Corporation and Gulfstream American Corporation for supplying flight manuals, cost data, drawings and aerodynamic data.

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SECTION 1

SUMMARY

The most significant improvements in small [under 2722 kg (6,000 lbm) gross weight] general aviation airplanes which have led to gains in providing essential services in the last two decades have been in the avionics realm. Advances in ground and airborne electronic devices, a by-product of massive federal support of military and space-related research, have made way for needed but as yet unrealized airplane performance, utility, and safety improvements.* The key to the needed airplane improvements is believed by many to lie with the small turbine engine, but small turbine engine technology is moving forward at a laggardly pace. The problem involves both financial and technical risks which the private sector is unwilling to take.

A Government-supported General Aviation Turbine Engine (GATE) program has been suggested as a means for stimulating the pace of small turbine engine development, but the mechanism for doing this is not clear. Initial GATE study activity has been directed toward delineating the proper content of a Government-sponsored program to develop and demonstrate advanced technologies for small general aviation turbine engines. The part of the study which was accomplished by WRC is covered in this document.

The present work develops a circa 1988 general aviation market scenario directed toward the postulation of advanced technology turboprop (T/P), turboshaft (T/S), and turbofan (T/F) engines and considers market needs, energy influences, and the regulatory environment. The postulated engines were then defined in terms of configuration, weight, size, performance, and cost through trade studies of the practicality of using a single gas generator as the core for each engine type. The study culminates in identification of long lead, key technology elements requiring attention in an advanced engine components research program, and a plan for such a program.

The market analysis projects a modest growth in general aviation <u>annual unit sales</u> through 1988 with pronounced <u>fleet growth</u> over the period because fleet additions can be expected to exceed retirements by a ratio of about five to one. This fleet growth will stimulate sales of airplanes capable of operating over a broader range of altitudes for traffic and weather avoidance. These airplanes of necessity will be pressurized, deiced, and faster than today's airplanes in order to deal with high altitude conditions. The turbine engine, and more specifically the turboprop, will probably be the popular engine of this era if cost and fuel economy constraints can be surmounted.

A family of low-cost, flat-rated T/P engines in the 134 to 261 kW (180 to 350 hp) class is foreseen as meeting the needs of the era. These engines, designed for long life and parts commonality, can play a prominent role in the new airplane

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*General aviation fatalities per million vehicle kilometers (or miles) is ten times that of the automobile.

and retrofit markets. Low cost would be realized through the exploitation of advantages gained from the relaxation of design stress and temperature levels (e.g., by the selection of alternate materials) and through a new and unique approach to component manufacturing. This approach requires that engine aerodynamic components be geometrically constrained to enhance producibility. The trade-off involves cost versus component efficiency and engine weight where the weight influence on marketability can be shown to be minimal. The requirement for geometric constraint affects axial compressor and turbine blading and involves constant camber, constant cross section, chord-taper, and twist considerations. A Government-sponsored research activity to maximize component aerodynamic efficiency through the optimization of the constrained geometry is suggested.

The performance of proposed T/P and T/F engines using a common core was defined to make possible airplane application and cost studies for evaluation of the merit of the engine concepts. These studies were made using the NASA-developed General Aviation Synthesis Program (GASP) and, for the T/P work, involved retrofitted contemporary single- and twin-engine airplanes. The studies showed that both the turboprop- and turbofan-powered airplanes exhibit significant life cycle cost (LCC) economies when compared with piston-powered counterparts, while demonstrating new dimensions in performance capability. Also, the T/P airplanes, if flown at high altitude, are more productive in terms of seat-km/l (seat-nm/gal). The major contributing factor to the LCC benefits is the lower turbine engine and turbine-powered airplane maintenance cost.

Until the present time there has been little government support for upgrading general aviation powerplant technology, and this can be justified in light of the evolving state of the national airspace system. This system is now quite sophisticated and getting more so with each passing day. The work here shows that general aviation, already a vital tool of commerce, is ready, owing to airspace system advances, to benefit from a new generation of powerplants. This technology needs to be nurtured through government support, however, because the risk is far more than industry is willing to accept.

SECTION 2

INTRODUCTION

A 1975 Federal Aviation Administration (FAA) census revealed that there were 171,156 active aircraft in the U.S. civil fleet and only 5 percent of these, including 39 percent of the helicopters, were turbine-powered. There were very few turbine-powered, fixed-wing airplanes in the under 2722 kg (6,000 lbm) weight class, a class dominated by airplanes with six or fewer seats and making up 90 percent of the entire general aviation fleet.

Despite such statistics, the marketing files of major turbine engine manufacturers bulge with airframe company inquiries about progress being made toward the development of potentially viable small T/P and T/F engines for general aviation. Pilots, too, are interested in progress in small turbine engines, because they are acutely aware of the benefits turbine power offers from a safety-of-flight/weather-avoidance standpoint.

The lack of small turbine-powered airplanes, despite designers' and pilots' intense interest in them, provides clear evidence that obstacles exist that are impeding their emergence. The acknowledged foremost obstacle is the lack of small turbine engines at a marketable cost. The high cost is influenced by development, tooling, materials, certification, and accessories costs. While operationally acceptable engines can be developed using traditional techniques, little competition is offered the less costly piston engine alternative. Clearly, a unique approach is needed to develop a small turbine engine that will make a significant market penetration.

Fuel efficiency is a second major obstacle inhibiting the proliferation of small turbine engines and is becoming increasingly significant with the steady advance in fuel prices. Yet, because of the superiority of the turbine engine from an operational standpoint, fuel consumption parity with the piston engine does not appear to be an absolute necessity. Airplane utility and productivity must be considered, in addition to the often misused seat-km/l (seat-nm/gal) parameter.

General aviation has made great progress over the last 30 years. The major part of this has to be attributed to advances in avionics and a modernization of the airport/airways system. More dramatic advances, abetted by the ongoing avionics revolution and a nearly 4 billion dollar accumulation in the Airport/Airways Trust Fund,* are promised for the future.

The under-2722 kg (6,000 lbm) airplane, which has undergone little change in three decades, needs new technology powerplants before it can realize a potential commensurate with that promised through avionics advances and airport/airways development. The airport/airways system can now handle modern, high-speed airplanes safely, and these airplanes can surely be built in small, fuel-efficient sizes if, and when, small turbine engines become available. A government stimulus through support of an advanced technology program is clearly needed to lessen

*Airport/Airways Trust Fund status as of 31 December 1978.

current business risks and revitalize a nearly stagnant small engine/small airplane technology. The payoff will be safer, more useful, superior performing general aviation airplanes that benefit from the advantages gained from new technology turbine powerplants. These airplanes will assure continued U.S. leadership of the world's general aviation market and place general aviation in a valued position among the various modes of transportation.

In an effort to explore ways to accelerate the emergence of small turbine engines, NASA has asked GATE contractors for assessments of the option to use a single gas generator as the core for T/P, T/S, and T/F engines. It has also asked for conceptual engines of the three types and the identification of critical components, high risk items, and long lead key technology elements. Recommendations are also sought with regard to an advanced engine components research program, including a schedule and projected costs for component design, fabrication and test, and an engine test program. The Williams Research Corporation answer to NASA's request for information is developed in the succeeding sections.

SECTION 3

STUDY PROCEDURES

The study postulated the future general aviation market to enable identification of the most appropriate turbine engine sizes and configurations for subsequent parametric work and conceptualization. It included engine and airplane conceptualization, performance predictions, and the evaluation of conceptual engines that could be adapted to a common core concept intended to attack the turbine engine cost problem. Technologies appropriate for Government sponsorship which would reduce engine development risks to levels acceptable for continuation work by private industry were identified, and a technology program plan was developed

In specific terms, the study was broken down into four major tasks identified as follows:

Task 1.0 Market Analysis
Task 2.0 Broad Scope Trade-off Studies
Task 3.0 Evaluation of a Common Core Concept
Task 4.0 Technology Program Plan

MARKET ANALYSIS

A circa 1988 market scenario for general aviation powerplants was forecast in accordance with a six-step approach that included:

1. Acquisition of available projections of the active fleet in 1988, including fleet composition, annual additions and the composition of added aircraft.

2. An assessment of the projections in the light of possible market influences involving energy availability, user charges, airport/airways development, the regulatory environment (including that associated with noise and emissions), economic regulations, new technology, and product liability.

3. Engine distribution projections by power level and type.

4. Identification of qualities lacking in present aircraft and aircraft powerplants that could influence the course of powerplant technology.

5. The postulation of advanced technology engines including desirable turbine engine sizes and configurations which take into account market needs, the potential retrofit market, energy influences, and the regulatory environment.

6. The determination of airframer interest in the postulated engines and an assessment of the potential impact of the postulated powerplants on the projected distribution of engines by power level and type.

Table I lists some of the information sources used for the market analysis and highlights specific data base material obtained from each.

At the conclusion of Task 1.0, candidate engines, airplanes, and mission profiles were identified for use as major inputs for performing the Broad Scope Trade-Off Studies.

BROAD SCOPE TRADE-OFF STUDIES

Parametric studies for projected 1988 state-of-the-art general aviation turbine engines were conducted, using mission profile and aircraft characteristics data developed during Task 1.0, to aid in engine cycle optimization and sizing analyses. Study limits involved T/S and T/P engines in the 112 kW to 746 kW (150 to 1,000 hp) range and T/F engines with cores sized comparably to the T/S engines. Emphasis was placed on propulsors producing less than 448 kW (600 hp) and on turbofans producing less than 6672 N (1,500 lbf) thrust.

TABLE I DATA BASE SOURCES

AEROSPACE INDUSTRIES ASSOCIATION (AIA)
(GA statistics)

AIRCRAFT OWNERS AND PILOTS ASSOCIATION (AOPA)
(Business jet noise)

AMERICAN PETROLEUM INSTITUTE (API)
(Impact of automotive diesel on fuel costs)

DEPARTMENT OF COMMERCE,
BUREAU OF CENSUS,
INDUSTRY DIVISION
(GA statistics)

ENVIRONMENTAL PROTECTION AGENCY (EPA)
(Aircraft noise and emission proposals)

FEDERAL AVIATION ADMINISTRATION (FAA)
(GA forecasts through 1988)

FEDERAL ENERGY ADMINISTRATION
(Fuel cost forecasts)

FLYING MAGAZINE ANNUAL
(GA airplane data)

FORECAST ASSOCIATES, INC.
(GA forecasts through 1982)

FOXJET INTERNATIONAL
(Advanced technology turbofan assessment)

FROST AND SULLIVAN, INC.
(GA forecasts through 1983)

GENERAL AVIATION MANUFACTURERS ASSN. (GAMA)
(Industries position regarding noise and emissions)

GULFSTREAM AMERICAN CORPORATION
(Cougar technical data and turbofan assessment)

HARTZELL PROPELLER, INC.
(Propeller cost, weight, and technology data)

HELICOPTER ASSOCIATION OF AMERICA, INC. (HAA)
(Helicopter engine—related safety information)

MOONEY AIRCRAFT CORPORATION
(Model 201 technical data)

NATIONAL BUSINESS AIRCRAFT ASSOCIATION (NBAA)
(Energy influence forecasts)

PIPER AIRCRAFT CORPORATION
(Aerostar 601P technical data)

THE WEEKLY OF BUSINESS AVIATION
(Historical and statistical information including annual airplane production figures)

WILLIAM P. LEAR, SR.
(Small turbofan engine/airplane assessment)

During the parametric work, conceptual layouts were made of T/P, T/S, and T/F engines, and a common core concept was developed. Candidate engine performance, weight, and cost estimates were made as the designs matured. Favored designs were subsequently mated with appropriate aircraft, and aircraft performance was calculated. The resulting performance was compared to desired characteristics data established during the Market Analysis and to the performance of piston-powered airplane counterparts. Finally, turbine engine-related life cycle costs were estimated and compared to corresponding piston engine-related life cycle costs.

Several steps were taken to develop high-confidence T/P airplane performance figures to enable value judgments to be formed on the merits of the proposed low-cost T/P engine from a fuel economy standpoint. These involved the mating (on paper) of the turboprop to existing airplanes, namely, the Aerostar 601P and the Mooney 201. Limited work was also done with the Gulfstream American Cougar.

Prior to calculating T/P airplane performance, the piston airplane performance was calculated using the NASA-developed General Aviation Synthesis Program (GASP). The GASP-derived data was baselined to FAA-approved airplane flight manual data for the airplanes of interest through appropriate input adjustments. The resulting inputs were used to calculate T/P airplane performance by means of GASP, with changes made only to account for airframe and powerplant differences (e.g., powerplant-, powerplant installation-, propeller-, and pressurization-related weights; propeller and nacelle size; and cooling drag).

EVALUATION OF A COMMON CORE CONCEPT

A core was sized and conceptualized and then T/P, T/S, and T/F extensions of the core were conceptualized. Performance, weight, and cost estimates were made for candidate T/P and T/F configurations and some candidates were eliminated on the basis of these estimates. Fuel efficiency and cost were emphasized in the T/P design, with weight considered of secondary importance since T/P engines tend to be much lighter than comparable piston engines. For some retrofit applications, a weight savings can be of dubious value because of airplane balance considerations (e.g., single engine airplane retrofits). Weight, however, is considered extremely important with respect to T/F designs, because these engines are typically aft-fuselage-mounted and excess weight aggravates airplane balance and stability problems.

Several iterations were made involving surviving concepts until a near optimum core was conceptualized which was common to a fixed-shaft turboprop, a conventional two-spool turbofan, and a free-turbine turboshaft.

TECHNOLOGY PROGRAM PLAN

A master schedule, portraying the logical and sequential development of the three types of turbine engines, was developed based on the common core design concept. The schedule was developed to provide the broad overview of GATE program activities necessary for successful delivery of certified engines which could meet the demands of general aviation in the late 1980's.

Besides the master schedule, several lower-tier schedules were formulated to illustrate the program planning in greater detail. Also, schedules were developed to show the proper content of a Government-sponsored program to develop and demonstrate advanced technologies for small-sized general aviation turbine engines. Critical components and high-risk items were identified and recommendations made as to the content of an advanced engine components research program.

An overall plan was developed that identifies schedules and the projected costs for component design, fabrication, and test. An engine test program was formulated and long-lead technology elements identified.

SECTION 4

MARKET ANALYSIS

Prior to the initiation of the market analysis to postulate a 1988 general aviation market scenario, a data base of pertinent recent publications was gathered to enable the most credible projections. Specifically, data was sought which would permit a breakdown of the current general aviation powerplant market into engine type and horsepower categories. Additionally, trends in emissions and noise regulations, energy constraints, user fees, and aircraft equipment and operating requirements were sought, together with existing government and industry forecasts.

AVAILABLE FLEET PROJECTIONS

Three documents were acquired that provided general aviation fleet projection data into the 1980's. Two of these furnished projections into the early 1980's and were prepared by private market research firms (ref. 1 and 2). The third was prepared by the Office of Aviation Policy of the Federal Aviation Administration (FAA-AVP) and provides projections through 1988 (ref. 3). The FAA projections were given the most weight because of the continuing work of FAA-AVP in the area of forecasts, forecasting methodologies, development of new data sources, and initiatives for involving members of the aviation community in forecasting for decision-making. Also, the FAA has privileged information through aircraft and engine type certificate applications that is not available to private market research firms.

Because FAA predictions are used in budgeting and managing the National Aviation System and by state, regional, and local decision-makers as well as by those in the aircraft industry, the forecasts tend toward being self-fulfilling. Table II provides the forecast of general aviation aircraft production in the United States developed as a baseline scenario by FAA. Total production figures derived from this scenario were ultimately adopted for use in the market analysis. Because FAA has developed alternative scenarios (e.g., an energy scenario and an economic stimulation scenario), factors were examined that could perturb the baseline scenario. These are discussed in Appendix A to put the market analysis in perspective.

ENGINE DISTRIBUTION PROJECTION

In order to estimate the fleet composition and attendant engine requirements by horsepower and type in 1988, the composition of fleet additions made in 1975 and 1976 was determined. Also such influences as current engine deficiencies that might affect the engine mix in 1988 were studied.

Key documents (ref. 4 through 8) were used to determine the 1975 and 1976 composition of engine deliveries for new aircraft by horsepower and type. These documents provide airplane delivery figures and associated engine data as

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TABLE II. FAA FORECAST OF GENERAL AVIATION AIRCRAFT PRODUCTION IN THE U.S.A. (BASELINE SCENARIO)

Fiscal Year	Piston		Turboprop Twin Engine	Turbojet Twin & Multi Engine	Rotary Wing Piston & Turbine	Total
	Single Engine	Twin & Multi Engine				
1972	6,901	1,305	132	74	444	8,856
1973	9,472	2,017	221	157	602	12,469
1974	11,092	2,158	560	199	721	14,730
1975	11,824	1,903	513	198	794	15,232
1976	12,150	1,879	616	186	615	15,446
1977T*	3,742	589	199	74	182	4,786
1977*	12,716	2,016	756	279	684	16,451
1978*	12,640	2,136	743	267	656	16,442
1979*	11,692	2,271	761	283	684	15,691
1980*	12,078	2,403	820	329	762	16,392
1981*	12,997	2,482	909	392	864	17,644
1982*	11,947	2,178	886	378	833	16,222
1983*	11,916	2,130	860	358	798	16,062
1984*	12,933	2,550	936	405	861	17,685
1985*	13,290	2,624	1,042	464	935	18,355
1986*	13,647	2,698	1,119	509	1,004	18,977
1987*	13,986	2,789	1,194	553	1,075	19,597
1988*	13,995	2,880	1,271	598	1,150	19,894

*Forecast

1977T*-- Is the transition quarter from 1 July 1976 through 30 September 1976.

NOTE--General aviation aircraft for export are included. All helicopter production, including air carrier transport helicopters, is included. (Total production figures and rotary wing production figures from this forecast adopted by WRC) supplied by Beech, Bellanca, Cessna, Gates Learjet, Grumman American (now Gulfstream American), Lake, Maule, Mooney, Piper, Rockwell, Ted Smith (now Piper), and Swearingen. A total of 16,260 engines delivered in 1975 and 17,768 engines delivered in 1976 were involved in the determination of engine distribution by type, (Figure 1). The engine distribution by kW (hp) involved 15,272 piston engines delivered in 1975 and 16,676 piston engines delivered in 1976.

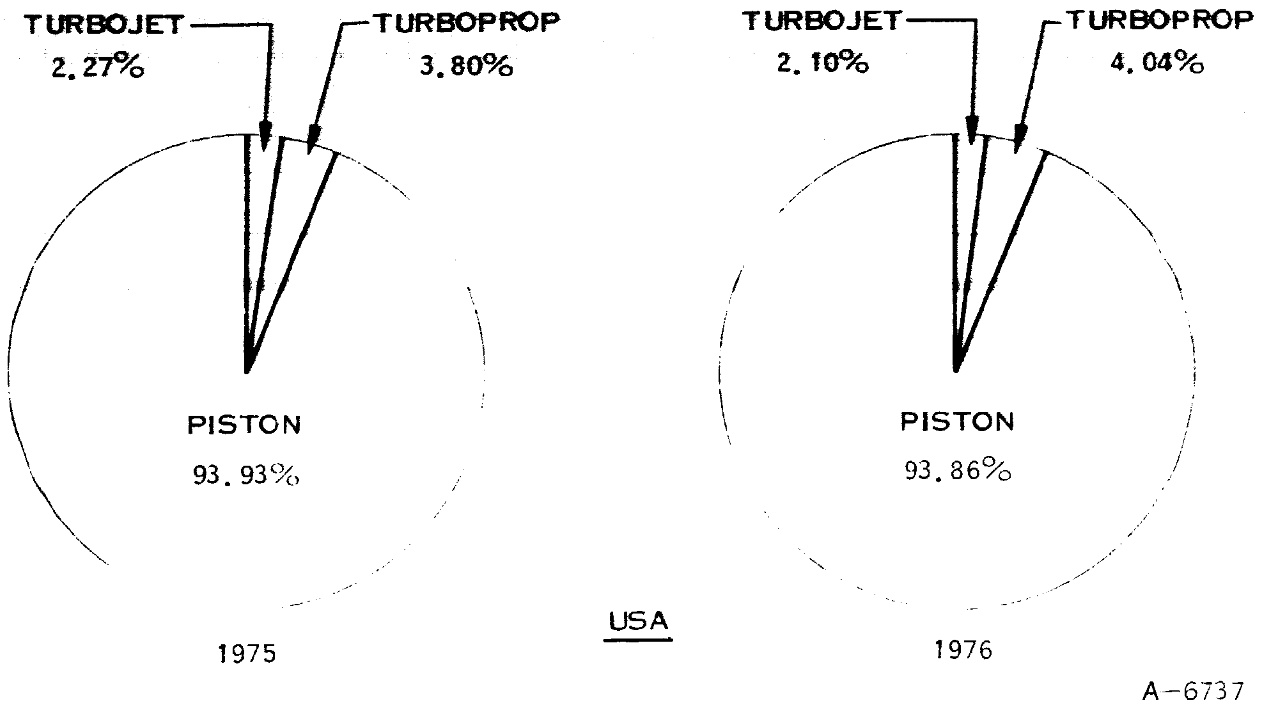

Figure 1. 1975 and 1976 General Aviation OEM Engine Sales by Type

Piston engine distributions by kW (hp) were determined for several combinations of kW (hp) ranges to demonstrate the sensitivity of the distributions to the specific ranges selected. Considerable sensitivity was noted when a range was shifted to include a popular aircraft model (Figure 2).

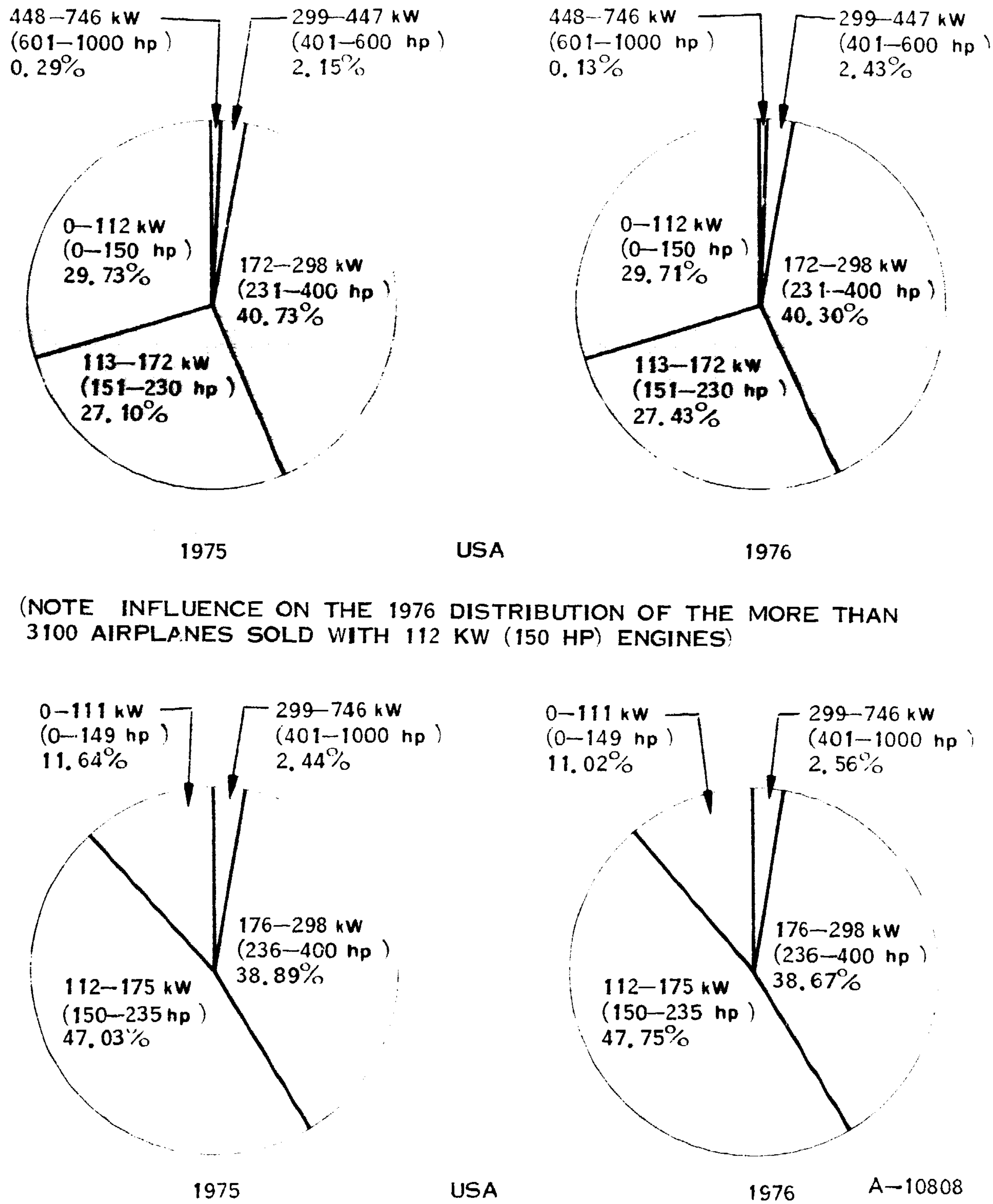

Figure 2. 1975 and 1976 General Aviation OEM Piston Engine Sales by Horsepower

A specific kW (hp) range combination was selected as a baseline for further work, (Figure 3). The selection was made on the basis of engine design studies that indicated the feasibility of producing at least three turboprop (T/P) powerplant models rated (flat-rated) between 134 and 231 kW (180 and 310 hp) using variants of a single, basic (T/P) engine design. The basic design, if developed to the point of being competitive with appropriately powered piston engines from a cost/fuel economy standpoint, would vie for 58 percent of the general aviation new-engine sales including the segment represented by 62 percent of the piston engines for newly manufactured aircraft.

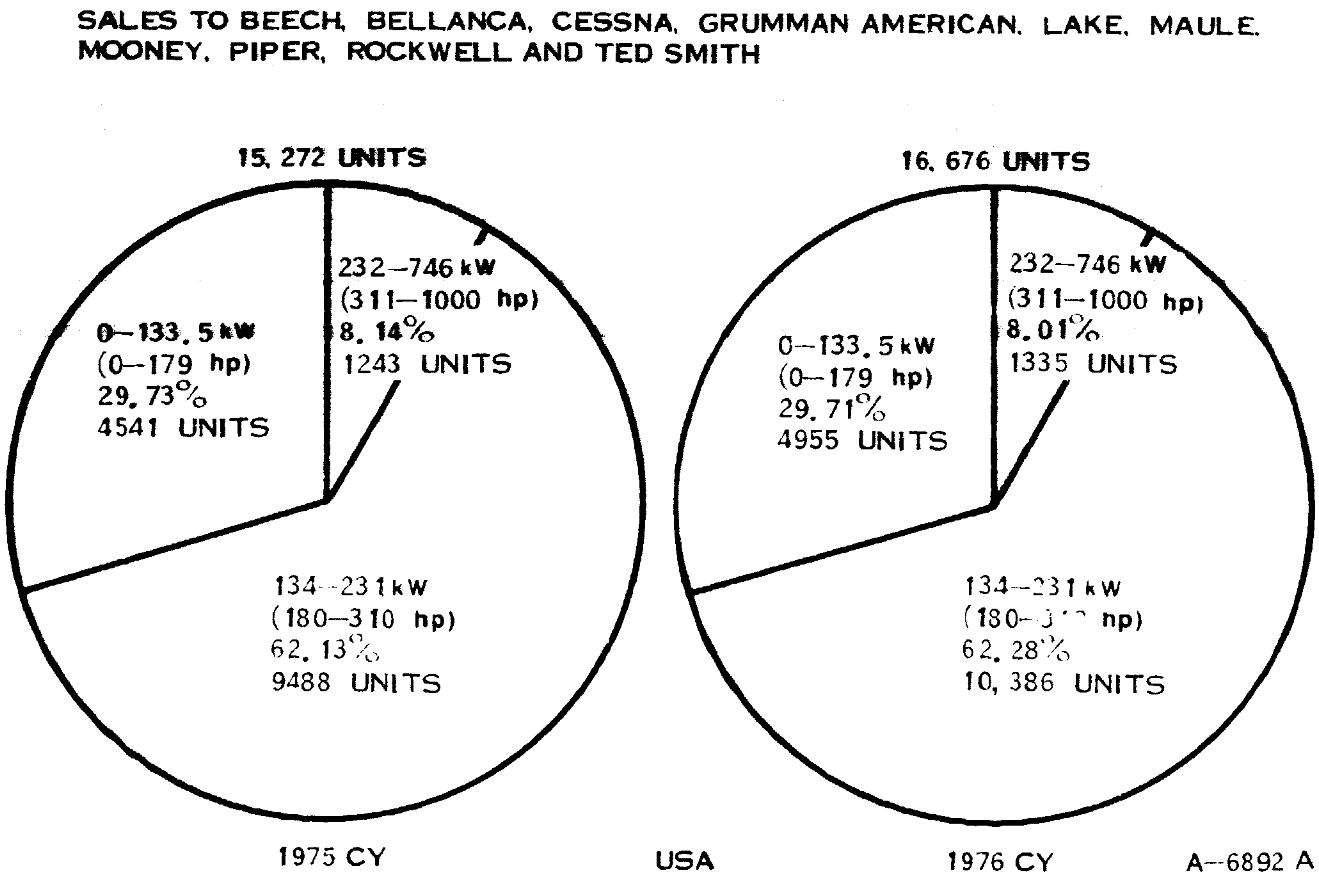

Figure 3. 1975 and 1976 General Aviation OEM Piston Engine Sales by Horsepower

The nearly identical 1975 and 1976 piston engine kW (hp) distribution data was assumed similar to what might be expected in 1988 whether the then existing engines are predominantly piston, turboprop, rotary, or other. The assumption of similarity was made in the face of several contradictory influences.

Rapidly escalating fuel costs, for instance, are influencing buyers toward the smaller, more fuel-efficient single-engine airplanes, and this trend is being supported by aircraft manufacturer actions to improve their airplanes aerodynamically. Also, actions are being taken to reduce the governed rpms of some engines because of a noise reduction need. The result, in some cases, has been that output power was reduced.

The projected increase in business-use sales relative to private-use sales, to the contrary, favor the large-engine and twin-engine airplane market. Also, the decreasing availability of 80-octane aviation gas caused engine manufacturers to discontinue the production of low kW (hp) engines (e.g., the Continental 0-200) or to uprate some of the low kW (hp) models to enable use of 100-octane low-lead avgas.

QUALITIES WANTING IN PRESENT AIRCRAFT AND AIRCRAFT POWERPLANTS

Piston engines produced for general aviation by Lycoming and Continental are, without a doubt, the finest available anywhere, as evidenced by major airframe manufacturer preferences. The general acceptance of these powerplants has led to their use in over 90 percent of the general aviation aircraft being built in the free world. Despite this unparalleled acceptance, there are a number of powerplant-related factors that limit the usefulness and affect the safety of contemporary general aviation aircraft. Some of these factors are unique to the piston engine and others apply equally to alternate means of propulsion. Detracting piston engine characteristics are listed in Table III Detracting features of turboprop (T/P), turbofan (T/F), and turboshaft (T/S) engines are shown in Tables IV, V and VI. The T/S performance deficiencies listed apply to specific U.S.-manufactured T/S engines producing less than 746 kW (1,000 shp). In the world market, there are several French-made T/S engines rated at less than 746 kW (1,000 shp) which are doing an excellent job in helicopters and which are making inroads into the U.S. market. These include the Turbomeca Astazou IIA, Artouste IIIB, and Arriel.

ADVANCED TECHNOLOGY ENGINE POSTULATION

A single factor, the ever-rising cost of fossil fuels, stands out as the key influence in the postulation of general aviation powerplants for the late 1980's. As a consequence, airplane fuel efficiency and utility must be stressed. Airplane fuel efficiency is emphasized, since installed engine performance is much more meaningful than, simply, engine performance. Engine weight and cooling drag along with specific fuel consumption have significance.

Engineers are prone to evaluate airplanes for fuel efficiency in terms of tangible parameters such as km/l (nm/gal) and seat-km/l (seat-nm/gal). These yardsticks, while having merit, exclude the influence of airplane performance on utility,

TABLE III. DETRACTING FEATURES OF PISTON ENGINES AND PISTON-POWERED AIRPLANES

• Cold weather starting is difficult, accelerates engine wear, and often requires engine preheat and/or external power.
• There is an overcooling tendency during rapid descents in cold air with the possibility of engine damage.
• Carbureted engines are subject to stoppage due to carburetor icing.
• Aircraft windshield defogging and cabin heat are commonly provided by an inherently hazardous exhaust-gas heat exchanger.
• Fuel-injected engines are a common cause of post-crash fires because of the dispersal and ignition of atomized fuel from broken injector tubes.
• Hot fuel-injected engines are difficult to restart because of injector tube vapor lock. Air restarts after the exhaustion of fuel from one tank and a switch to a second tank can be excessively time-consuming.
• Engine vibrations cause airframe fatigue cracks, tube and wire chafing, and limit propeller TBO to about 1,000 hours. (T/P propellers typically have 3,000 hour TBO's.)
• Piston engines, especially turbocharged piston engines, are heavy and bulky.
• Metal propellers are heavy, easily nicked, and deserving of respect by ground personnel, passengers, and crew.
• The excessive thrust lapse rate with airspeed of propeller-driven, piston-powered airplanes constrains cruise performance and limits the volume of airspace available to the pilot for weather avoidance and passenger comfort.
• Propellers produce torque, gyroscopic moments and yawing moments at low flight speeds (due to "P" effect), making the piloting task more difficult.
• Contemporary engine/propeller combinations produce excessive noise, especially in the aircraft cabin (typically 88-97 dB(A)).
• Engine-out asymmetrical thrust on twin-engine, propeller-driven airplanes creates a condition requiring adept piloting. (Note: Reducing propeller/fuselage clearance and the attendant yawing moment due to asymmetrical thrust results in high in-cabin noise levels.)
• Landing gear length and weight is sometimes influenced by propeller ground clearance requirements with an attendant influence on available wing volume for fuel storage in retractable gear airplanes.
• Piston engine cooling drag is excessive (typically 5 to 20 percent of cruise drag) and propeller performance is degraded by after-body influences.
• Turbocharged piston engines are complex when compared to turbine engines, cause under-cowl crowding, are substantially more costly to maintain than corresponding nonturbocharged models, and generally are not as fuel-efficient as nonturbocharged engines unless particular flight profiles are followed.
• Piston-powered airplanes require multiple powerplant controls (e.g., throttle, propeller, mixture, carburetor heat, and cowl flaps), thus adding to pilot work load.

TABLE IV. DETRACTING FEATURES OF CONTEMPORARY TURBOPROPS

• A high first cost which tends to drive airplane cost beyond the means of most small airplane operators.
• High overhaul costs (typically 50 to 70 percent of new engine cost).
• High specific fuel consumption [typically 0.34 to 0.38 kg/kW-h (0.56 to 0.63 lbm/hp-h) at takeoff rating].
• High fuel consumption for flight operations at altitudes below 15,000 feet where most non-instrument-rated pilots (71 percent of all pilots) operate.
• Vulnerability to inlet icing and FOD.
• Fixed-shaft models are noisy, especially during ground operations. In-cabin noise levels exceed turbofan airplane cabin noise levels.
• Metal propellers are heavy, easily nicked, and deserving of respect by ground personnel, passengers, and crew.
• The thrust lapse rate with airspeed is excessive.
• Propellers produce torque, gyroscopic moments, and yawing moments at low flight speeds (due to "P" effect) making the piloting task more difficult.
• Engine-out asymmetrical thrust on twin-engine, propeller-driven airplanes creates a condition requiring adept piloting (Note: Reducing propeller/ fuselage clearance and the attendant yawing moment due to asymmetrical thrust results in high in-cabin noise levels.)
• Landing gear length and weight is sometimes influenced by propeller ground clearance requirements with an attendant influence on available wing volume for fuel storage in retractable gear airplanes.
• Ground starts with a dead battery and without external power are not possible. The engine cannot be hand-propped for starting.

TABLE V. DETRACTING FEATURES OF CONTEMPORARY TURBOFANS

• A high first cost which tends to drive airplane cost beyond the means of most small airplane operators.
• Excessive fuel consumption.
• Vulnerability to inlet icing and FOD.
• Excessive performance degradation due to high temperatures.
• Inadequate takeoff thrust for small airport operations.
• Idle thrust is sometimes excessive.
• Responsiveness for go-arounds is poorer than piston and turboprop engines.
• Thrust-reversing capability is expensive to incorporate.
• Windmilling starts can involve considerable altitude loss.
• Ground starts with a dead battery and without external power are not possible.

TABLE VI. DETRACTING FEATURES OF CONTEMPORARY U.S.A. TURBOSHAFT ENGINES BELOW 746 kW (1000 shp)

• High first cost.
• High overhaul cost.
• Excessive performance degradation due to high temperature and altitude in combination with inadequate performance reserve.
• Inadequate engine life because many operations are carried on at, or near, maximum rated power.

safety, the quality of ride, and the time necessary to make a trip. Indeed, the atmosphere within which airplanes fly is not homogeneous, nor is it two-dimensional. Flight is conducted in three dimensions, and within that airspace violent weather capable of tearing airplanes apart as well as quiescent serenity can be found. The ability of an airplane to operate clear of stormy areas is of paramount importance to passengers and crew alike, and this ability relates to the power available for climb and operations at high altitude. Considerable fuel is routinely saved by flying over bad weather instead of circumventing it. The J-3 Cub can be described as very fuel-efficient in terms of the km/l (nm/gal) and seat-km/l (seat-nm/gal) yardsticks, but is hardly competitive as a useful people-moving conveyance except for very specialized applications. Intangibles cannot be overlooked when the subject is airplane fuel efficiency.

Because altitude capability is the key to passenger-carrying utility, the general aviation powerplant of the future must permit rapid climbs to high altitude while supplying the power needed for avionics, cabin pressurization, and ice removal. Fuel efficiency does not become totally relevant until these prerequisites are met. Engine flat rating to 4,572 m (15,000 ft) or more altitude and bleed air availability with minimum performance degradation could be key considerations.

In the past, businesses have had to purchase airplanes that were, perhaps, larger than needed in order to move about in a manner rivaling the airlines for schedule reliability and comfort. [The average business jet flight carries 3.4 passengers about 891 km (481 nm]. This was simply because there were no small airplanes having adequate performance capability. Airport/airways system improvements, together with rapid developments in avionics and instrumentation, now make possible the development of small airplanes that can move about with the surety of larger airplanes while saving considerable fuel in the process. Candidate engines for these airplanes need not have superior fuel specifics, although close-to-large-engine and piston-engine economy are desirable. Fuel can be saved simply by matching airplane size to the passenger-carrying requirements of business. Additional fuel can be saved if the small airplane can be made easy enough to fly to permit the businessman to fly it himself. Small airplane productivity, in terms of passenger seat-km/l (seat-nm/gal), can hardly be considered acceptable when professional crew members occupy as many as one-third of the available seats. With continuing advances in avionics, autopilot technology, airplane and powerplant design, weather observation techniques, and air traffic control, there should be less need for professional crews in small airplanes in the late 1980's than today. Perhaps at some point, professional small airplane pilots will be no more needed than chauffeurs for the family automobile.

In selecting a general aviation turbine engine type and size for the late 1980's, expected unit sales and sales price become key considerations. Sales-related matters involve the adaptability of the engine to single-engine and multi-engine airplanes, and to the retrofit market. The type of flying expected during the era will also influence the choice of engine type/size. Current trends suggest that instrument and night flying will be routine, with an attendant demand for systems redundancy (e.g. avionics, electrical, hydraulic) and twin engine reliability. Unfortunately, high fuel and engine/airplane costs will counter this demand.

Single-engine instrument and night flying require high equipment reliability. Purely routine operations can be shattered by communication, electrical system, or powerplant malfunctions, and the possibility of these has a sobering psychological influence on pilots and passengers alike. Most experienced instrument-rated pilots would prefer the added safety provided by two engines, two alternators or generators, two communications transceivers, etc. Consequently, any synthesis of a fuel-efficient airplane sized for the travel requirements of business and capable of airline-like ontime performance must include two properly sized engines. Few large-corporation presidents will travel routinely in single-engine airplanes. They may be willing to ride in small twin-engine airplanes, however, if trips can be made swiftly, safely, and comfortably.

In adapting turbine engines to a retrofit market as well as to new single- and twin-engine airplane designs, the turboprop has more merit than the turbofan. This is because of the relative ease with which turboprops can be substituted for piston engines in existing designs (especially twin-engine airplanes). As a result of the light weight of candidate turboprop engines, variants of a single basic turboprop engine design have the potential for use in all newly manufactured, four-to-seven-place, single-engine airplanes and twins seating up to ten persons. This kind of adaptability yields significant cost and maintainability benefits. The lightweight turboprop, in combination with new lightweight Kevlar propellers (blade weight 60 percent of aluminum), will also cause twin-engine preferences to evolve toward the safer centerline thrust configurations such as the Rutan Defiant. These designs will be structurally more attractive (lower wing root bending moments) than their piston counterparts. Also, weather radars that can look through propellers or be wing- or tail-mounted are already providing a formerly unavailable capability for push-pull configurations, which is adding to their attractiveness.

Offsetting the merits of turboprops is the expected lower cabin noise level attainable with rear-mounted turbofans. The exact value of a quieter cabin to the business executive is hard to assess against the probable higher fuel consumption of the turbofan, but it might be an overwhelming influence. Our hypothetical executive can ill afford the fatigue induced by high noise levels, or the throat fatigue and hoarseness which result from conversing in a noisy atmosphere.

TURBOPROP ENGINE DESIGN CRITERIA

The postulated turboprop engine is a 73-kg (160-lbm)*, fixed-shaft unit capable of filling the 134 to 231 kW (180 to 310 hp) market niche. It would be flat-rated, even for 231-kW (310-hp) applications, to enable it to compete with turbocharged piston engines. After considering weight and cooling drag advantages, the installed fuel efficiency must be competitive with the piston engine at nominal cruise conditions and excel over the piston at high altitudes. Life cycle cost must be competitive with turbocharged piston engines, and first cost must be lowered through manufacturing economies.

A proposed approach for reducing manufacturing costs and providing low maintenance and high saleability involves a fixed-shaft, low-speed, low-stress design concept. This concept utilizes a low-speed, multistage axial compressor with a

*Less starter-generator

design tip speed of 259 m/s (850 ft/s) followed by a centrifugal compressor. The low-speed feature, in which all elements run subsonically, produces excellent efficiency and low noise levels. The high hub/tip ratio and the many blades put the frequencies in an easily handled category.

The compressor rotor consists of an axial component coupled directly to a low-pressure ratio centifugal compressor having all-radial elements. A two-stage inducer is a part of the axial component. The compressor is followed by a very lightly-loaded burner with ample volume to incorporate emissions-reducing contro-vances. The fuel injection system is a shaft-mounted nozzle system that provides the advantages of very high injection pressures with low-cost fuel control concepts. The turbine is a lightly-loaded, four-stage unit conceived as a companion for the low-speed, low-stress compressor rotor.

TURBOFAN ENGINE DESIGN CRITERIA

The postulated turbofan engine is an 84-kg (185-lbm), two-spool unit capable of producing approximately 4448 N (1,000 lbf) of thrust under static, sea level, standard day conditions. It would use the low-cost turboprop gas generator as a major core component. The bypass ratio would be in the 4 to 5 range and the overall pressure ratio over 20. The engine would be optimized for a 9144 m (30,000 ft), Mach 0.6 mission and would fill the powerplant need of a six-place business jet which can be flown safely and inexpensively by a non-professional pilot.

The turbofan engine design employs a fan having a maximum tip speed of approximately 305 m/s (1,000 ft/s), which produces pressure ratios to 1.4 under standard conditions. The fan is attached to and followed by a three-stage intermediate-pressure (IP) compressor of about a 28°K (50°F) temperature rise per stage. This modest temperature rise enables the manufacture of the IP rotor in accordance with low-cost construction concepts. The IP compressor and fan are driven by a four-stage, low-speed turbine. The engine accessories are arranged around the waist formed by the axial compressor rotor of the core.

TURBOSHAFT ENGINE

The postulated turboshaft engine is a free-turbine design with the free turbine driving a simple 6,000 rpm output gearset and a high-speed accessory drive. The weight would be about 77 kg (170 lbm) and it would produce about 373 kW (500 shp) and be flat rated to about 2438 m (8,000 ft).

POTENTIAL IMPACT OF POSTULATED ENGINES

As the result of the marketing study and airframer contacts, a forecast showing the possible influence of powerplant technology advances on aircraft production by type of aircraft was made. This projection, Table VII, is considerably different from the FAA baseline scenario, (Table II), which projects a more leisurely pace in powerplant technology advances. The assumptions used to develop Table VII are as follows:

TABLE VII. GENERAL AVIATION AIRCRAFT PRODUCTION IN THE UNITED STATES*

Year	Fixed Wing						Rotorcraft		Total
	Piston		Turboprop		Turbofan		Piston	Turboshaft	
	Single-engine	Twin-engine	Single-engine	Twin-engine	Single-engine	Twin-engine			
1977	12,929	2,230	-	413	-	195	228	456	16,451
1978	12,944	2,233	-	414	-	195	219	437	16,442
1979	12,306	2,123	-	393	-	185	228	456	15,691
1980	12,816	2,211	1	409	-	193	254	508	16,392
1981	13,756	2,411	4	414	-	195	288	576	17,644
1982	12,587	2,154	30	419	2	197	278	555	16,222
1983	12,327	2,090	176	447	13	211	266	532	16,062
1984	12,997	2,207	743	558	56	263	287	574	17,685
1985	11,837	1,873	2,276	859	171	404	312	623	18,355
1986	9,292	1,169	5,065	1,405	381	661	182	822	18,977
1987	6,386	369	8,186	2,016	616	949	28	1,047	19,597
1988	5,041	0	9,606	2,294	723	1,080	0	1,150	19,894

***Assumes competitively-priced, fu efficient, T/P, T/F, and T/S engines will emerge in mid-1980's. Projections will not materialize without vigorous GATE funding.**

1. Competitively-priced, fuel efficient, turboprop, turboshaft and turbofan engines will emerge starting in the mid-1980's as a result of the NASA GATE program and related manufacturer activities.

2. The FAA forecast of total general aviation aircraft and rotorcraft production through 1988 is correct (Table II). This forecast is related to the ability of the airport/airways system to safely assimilate additional aircraft. It is an FAA tool for long-range planning and for funding acquisition for system upgrading. It tends toward self-fulfillment.

3. Twin-engine, fixed-wing aircraft will continue to constitute only about 18 percent of total fixed-wing aircraft production despite an increasing demand for system redundancy. Economic factors, particularly fuel costs, will exert a constraining influence.

4. Single-engine, fixed-gear airplanes having less than 134 kW (180 hp), for the most part, will continue to be piston-powered. This is because engine manufacturer interest will focus on turbine engine replacements

for piston engines in the 134 to 231 kW (180 to 310 hp) range. Single-engine airplane replacement engines will be predominantly turboprop. Turboprops will be preferred over turbofans for the following reasons.*

a. Improved takeoff acceleration needed for operations from the many general aviation airports having short runways.

b. The very short landing capability provided by propeller thrust reversal.

c. The weight and balance advantages gained from a nose-mounted engine.

d. Better fuel economy than a turbofan.

e. The added airplane controllability and responsiveness permitted by slipstream influences on the tail control surfaces. This can be particularly useful in salvaging bad landings.

5. Thirty-two point eight percent of single engine airplanes will have less than 134 kW (180 hp). (1976 figure)

6. An estimated seven percent of the single engine turbine airplanes will be turbofan-powered. These will fill the high-performance market niche.

7. An estimated thirty-two percent of the twin turbine airplanes will be turbofan-powered. The greater fuel efficiency of the turboprop will be offset by the quieter cabin and greater ease and safety with which a twin-turbofan-powered airplane can be flown by a nonprofessional pilot, particularly under engine-out situations. The single-pilot-flown, small, twin-turbofan airplane will prove very popular as a business tool.

8. By 1988, all newly manufactured, twin-engine airplanes will be turbine-powered.

9. Two-thirds of the helicopters manufactured during the 1977 through 1985 time period will be turboshaft-powered. By 1988, all newly manufactured helicopters will be turboshaft-powered.

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*Customer preference might radically affect the turbofan/turboprop balance if the turbofan lives up to its expectations in minimization of cabin noise. This factor has not yet been adequately assessed.

Table VIII forecasts the annual production of general aviation piston, turboprop, turbofan, and turboshaft engines through 1988. Quantities are shown for engines installed in new aircraft, and for the estimated total production for fulfilling new aircraft, replacement, and retrofit market needs. This table is supplemented by an assumptions list, and it has been developed by using the aircraft production figures in Table VII as a basis. The assumptions used to develop Table VIII are as follows:

A. Engines For New U.S.A.-Produced Aircraft

1. Piston engine production for new fixed-wing, piston-powered airplanes equals the sum of single-engine airplane production plus two times twin-engine airplane production. Turboprop and turbofan engine production was figured similarly.

2. T/S engine production for new rotorcraft was computed by multiplying the total civil T/S-powered helicopter production by the factor 1.258, where 1.258 equals the sum of total civil T/S helicopter production plus total civil twin-engine T/S helicopter production divided by total civil T/S helicopter production for the year 1975. (ref 10).

3. Piston engine production for new rotorcraft was assumed equal to the civil piston-powered helicopter production, since virtually all civil piston-powered helicopters produced are single-engine models that fall in the general aviation category.

B. Total Engine Production for New U.S.A.-Produced Airplanes and for the Replacement and Retrofit Markets

1. Total piston engine production for fixed-wing airplanes for the years 1977 through 1985 equals 1.3 times piston engine production for new fixed-wing airplanes. Total piston engine production for fixed-wing airplanes for the years 1986, 1987, and 1988 equals the piston engine production for new fixed-wing airplanes plus 5,085. The 5,085 equals the annual average of forecasted piston engine production for replacement purposes for the nine years starting in 1977. Relatively constant replacement market is projected due to a nearly static piston fleet growth, gradually increasing piston TBOs, and static or declining piston airplane utilization rates as the result of escalating fuel costs and increasing simulator use.

2. Total T/P engine production equals 2.6 times the twin T/P airplane production plus 1.1 times the single T/P airplane production. These figures reflect the need for replacement engines for the existing T/P fleet and expected higher utilization rates of twin T/P airplanes.

3. Total T/F engine production equals 2.6 times the twin T/F airplane production plus 1.2 times the single T/F airplane production. These

TABLE VIII. PROJECTED GENERAL AVIATION AIRCRAFT ENGINE PRODUCTION*

A. Engines for New Aircraft

Year	Fixed Wing			Rotorcraft	
	Piston	Turboprop	Turbofan	Piston	Turboshaft
1977	17,389	826	390	228	574
1978	17,410	828	390	219	550
1979	16,552	786	370	228	574
1980	17,238	819	386	254	639
1981	18,578	832	390	288	725
1982	16,895	868	396	278	698
1983	16,507	1,070	435	266	669
1984	17,411	1,859	582	287	722
1985	15,583	3,994	979	312	784
1986	11,630	7,875	1,703	182	1,034
1987	7,124	12,218	2,514	28	1,317
1988	5,041	14,194	2,883	0	1,447

B. Total Engine Production

Year	Fixed Wing			Rotorcraft	
	Piston	Turboprop	Turbofan	Piston	Turboshaft
1977	22,606	1,074	507	296	746
1978	22,633	1,076	507	285	715
1979	21,518	1,022	481	296	746
1980	22,409	1,065	502	330	831
1981	24,151	1,081	507	374	942
1982	21,964	1,122	515	361	907
1983	21,459	1,356	564	346	870
1984	22,634	2,268	751	373	939
1985	20,258	4,737	1,256	406	1,019
1986	16,715	9,224	2,176	261	1,344
1987	12,209	14,246	3,207	107	1,712
1988	10,126	16,531	3,676	79	1,881

*Projections will not materialize without vigorous GATE funding.

figures reflect the need for replacement engines for the existing T/F fleet, an expected earlier introduction of the GATE T/F in twin engine aircraft than in singles, and a higher expected average twin utilization rate.

4. Total piston engine production for helicopters for the years 1977 through 1985 equals 1.3 times the piston engine production for new helicopters. Total piston engine production for helicopters for the years 1986, 1987, and 1988 equals the piston engine production for new helicopters plus 79. The 79 equals the annual average of forecasted piston engine production for replacement purposes f r the nine years starting in 1977. A nearly constant replacement market is projected due to an expected decline in piston helicopter fleet growth and gradual increases in piston TBOs.

5. Total T/S engine production equals 1.3 times the T/S engine production for new helicopters.

The potential sales of turboprop engines in the 134- to 231-kW (180- to 310-eshp) class for the year 1988 are shown in Table IX, together with a list of assumptions. The reality of this number of turboprop unit sales can be influenced decidedly by the course of the GATE program and by the success achieved in overcoming turbine engine cost/fuel economy problems.

TABLE IX. POTENTIAL SALES OF TURBOPROP ENGINES IN THE 134 to 231 kW (180 to 310 eshp) SIZE CLASS IN THE YEAR 1988*

Number of Units for New Aircraft	= 11,852
Total Unit Sales	= 13,803

Assumptions:

1. A competitively-priced, fuel efficient turboprop will emerge in the mid-1980's which will assume the propulsion task currently being performed by 134 to 231 kW (180 to 310 hp) piston engines.

2. In 1988, 83.5 percent of the turboprop engine production will be for airplanes requiring 134 to 231 kW (180 to 310 eshp) powerplants (1976 figure for OEM powerplant deliveries involving propulsors that drive propellers).

3. The 134 to 231 kW (180 to 310 eshp) propulsor requirement can be satisfied by three or four variants of a single, basic turboprop engine design. The models will be flat-rated to permit operation over a wider altitude spectrum than nonturbocharged piston counterparts.

*Projections will not materialize without vigorous GATE funding.

Figure 4 shows the potential influence of the GATE program on the 1988 engine sales mix by type for new-production, fixed-wing aircraft. Without a significant technology advance, the FAA projection would appear to be the most plausible, but through the nurturing of specific technology elements, a trend toward the projection at the bottom of the figure is likely. The rate of progress in this direction depends a great deal on resource allocations.

To develop turbine engine cost goals in 1977 dollars, the list prices of several Lycoming piston engines were estimated using a 1975 price list and specific post-July 1977 list price data for the Lycoming 0-360 A1D four-cylinder engine and the 0-540 A1A5 six-cylinder engine. Four- and six-cylinder engine list prices were estimated by multiplying 1975 prices by appropriate ratios as determined for the specific engines. The 1977 price list generated by this approach is shown in Table X.

TABLE X. APPROXIMATE LIST PRICES FOR NEW AND REMANUFACTURED LYCOMING PISTON ENGINES - 1977 DOLLARS

Engine	Approx kW (hp)	New Outright	New Exchange	Rmfg Exchange
0-235C, C1	86(115)	5,188	4,458	3,896
0-320A, B	112/119(150/160)	5,912	5,084	4,446
0-360A Series	134(180)	6,723	5,782	5,047
0-360A4G, A4J, A4K	134(180)	6,692	5,751	5,032
0-540A Series	186(250)	9,636	8,284	7,224
0-540B Series	175(235)	9,414	8,092	7,061
0-540E	194(260)	9,434	8,112	7,071
IO-320 B1A	119(160)	8,427	7,244	6,332
IO-320 C1A	119(160)	9,143	7,896	6,897
IO-320 E Series	112(150)	7,806	6,716	5,864
LIO-320 B1A	119(160)	8,689	7,470	6,527
LIO-320 C1A	119(160)	9,571	8,229	7,195
IO-360 A1A	149(200)	8,945	7,696	6,728
IO-360 B4A	134(180)	8,329	7,129	6,255
IO-360 C1C	149(200)	8,781	7,552	6,594
LIO-360 C1E6	149(200)	9,828	8,450	7,380
IO-540 A, E Series	216(290)	12,988	11,167	9,737
IO-540 C4B5	186(250)	10,908	9,378	8,17[illegible]
IO-540 G Series	216(290)	13,525	11,630	10,146
GO-435 C2,C2B,C2C	194(260)	18,710	16,090	14,029
GO-480 D Series	220(295)	19,765	16,997	14,823
GO480 G Series	220(295)	19,415	16,696	14,556
GSO-480 B Series	254(340)	25,049	21,284	17,528
IGO-540	261/283(350/380)	22,850	19,416	15,990
TIO-540 A2C	231(310)	20,154	17,332	15,113
IGSO-540A, A1A	283(380)	27,784	23,615	19,445

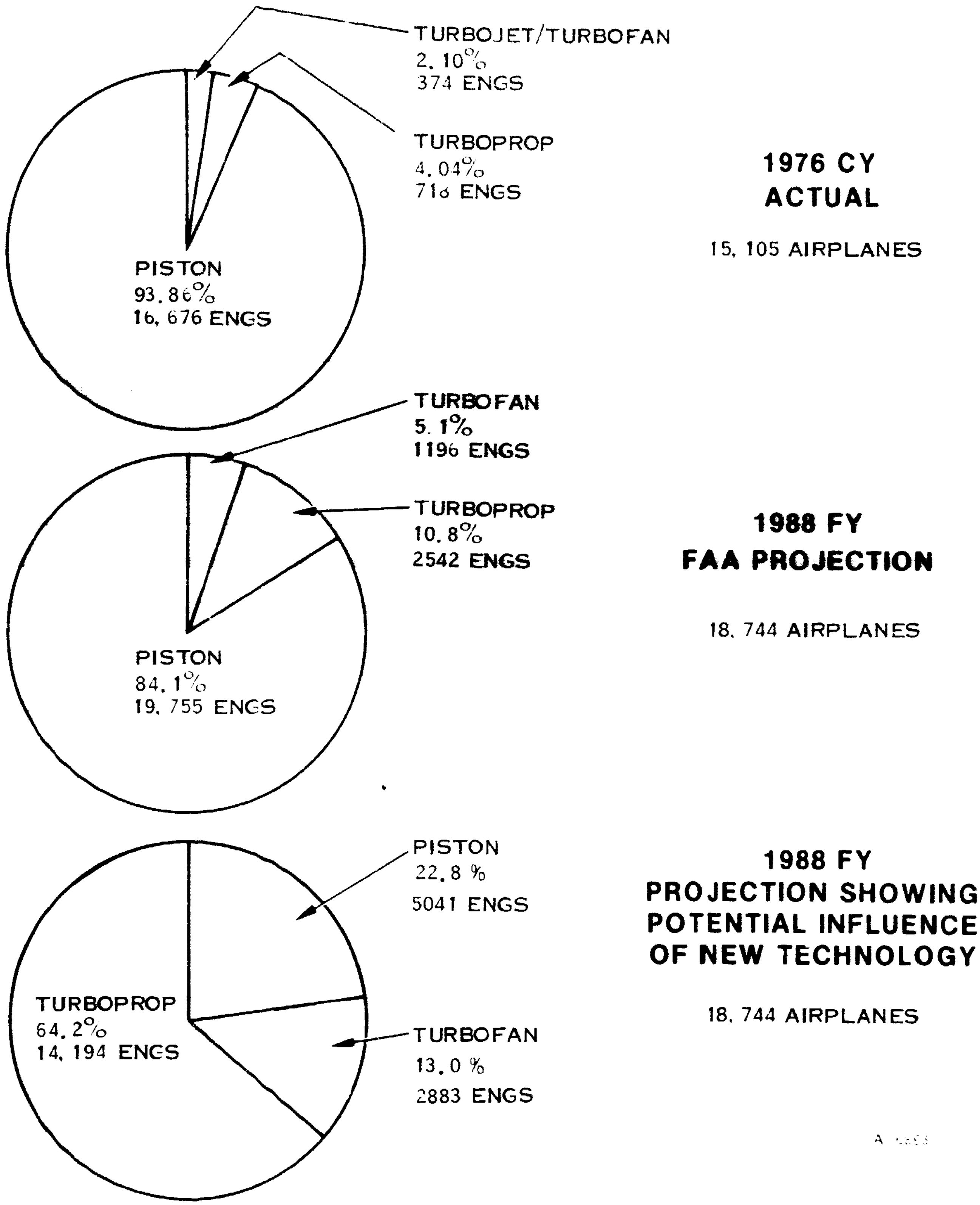

Figure 4. Projected Influence of New Technology on OEM Engine Sales by Type for Fixed-Wing Aircraft (USA)

Meaningful piston engine, turboprop and turbofan cost comparisons cannot be made without the addition of propeller prices to the piston and turboprop engine prices. Consequently, propeller list price data was obtained from Hartzell Propeller, Inc. Typical figures that exclude anti-ice and deice provisions are shown in Table XI. For cost comparison purposes, the cost to provide for turbofan cowl anti-icing can be assumed to approximate propeller anti-icing equipment costs.

Typically, engines and propellers are sold to original equipment manufacturers at 60 percent of list price. The data provided in Table X, therefore, can be translated into meaningful, albeit somewhat oversimplified, cost goals for a turboprop engine family. The combined data of Tables X and XI have to be used judiciously to establish turbofan engine cost goals, however, because of the higher characteristic cruise-thrust/takeoff-thrust ratio of turbofans relative to turboprop and piston propulsors.

TABLE XI GENERAL AVIATION PROPELLER DATA*
(SI Units)

Type Propeller	Engine kW Range	Dia Range (cm)	Weights (kg)	List Prices ($)
Two-Blade, Constant-Speed	134-194	183-249	27.7-34.9	1,160-1,595
Two-Blade, Feathering	119-186	183-208	28.1-34.0	1,380-1,520
Three-Blade, Constant-Speed	213-261	208-249	39.9-54.4	1,685-2,360
Three-Blade, Feathering	194-336	188-244	37.6-56.7	2,025-2,755
Three-Blade, Reversible, Feathering	236-671	213-274	53.5-64.9	3,030-3,965
Four-Blade, Reversible, Feathering	507-533	229-254	69.9	4,695-5,005
Five-Blade, Constant-Speed, Reversible, Feathering	835	282	98.9	5,805
Anti-icing or Deicing Provisions				Optional at added cost

*Source: Hartzell Propeller, Inc. - Piqua, Ohio, 1977.

NOTE: OEM price approximates 60 percent of list.

TABLE XI. GENERAL AVIATION PROPELLER DATA*
(English)

Type Propeller	Engine hp Range	Dia Range (in)	Weights (lb)	List Prices ($)
Two-Blade, Constant-Speed	180-260	72-98	61-77	1,160-1,595
Two-Blade, Feathering	160-250	72-82	62-75	1,380-1,520
Three-Blade, Constant-Speed	285-350	82-98	88-120	1,685-2,360
Three-Blade, Feathering	260-450	74-96	83-125	2,025-2,755
Three-Blade, Reversible, Feathering	317-900	84-108	<118-143	3,030-3,965
Four-Blade, Reversible, Feathering	680-715	90-100	154	4,695-5,005
Five-Blade, Constant-Speed, Reversible, Feathering	1120	111	218	5,805
Anti-icing or Deicing Provisions				Optional at added cost

*Source: Hartzell Propeller, Inc. - Piqua, Ohio, 1977.

NOTE: OEM price approximates 60 percent of list.

MISSION PROFILE CONSIDERATIONS

There are several considerations meriting attention with respect to the selection of mission profiles for general aviation aircraft in 1988. These involve the expected fleet size, the national airspace system, and the level of technology. The general aviation fleet size, for instance, is projected by FAA to increase from about 181,600 active aircraft at the end of 1976 to about 267,000 in 1988 (ref. 3). This 47 percent increase is expected to be accompanied by an 89 percent increase in hours flown and an 88 percent increase in instrument operations. The 1988 airspace will therefore be more congested than it is today and the traffic separation problem will be more acute.

In the instrument environment, traffic is separated longitudinally, vertically, and laterally. Participating pilots flying unpressurized airplanes are frequently limited in their selection of suitable altitudes because of weather and the capability of their aircraft [90 percent of the earth's weather occurs below 3048 m (10,000 ft)]. Altitude options may be excluded, for example, because of the likelihood of airframe icing in specific strata. With increasing traffic, fewer pilot altitude requests can be granted on a timely basis because of conflicts with other traffic. Also, alternate, less safe, less comfortable altitudes will sometimes be assigned by air traffic control. The reduced availability of preferred altitudes in the lower strata in 1988 will therefore cause airplane buyer interest to shift toward airplanes that can be operated efficiently over a wider spectrum of altitudes. These airplanes will have pressurized cabins and cruise speeds sufficiently high to minimize the effects of headwinds at high altitude. The popular airplane of the era will also have been certified for flight in known icing conditions because icing is a common occurrence during cloud penetrations at temperatures below 273°K (32°F).

The 89 percent increase in expected hours to be flown in 1988 will cause more congestion of traffic flying under visual flight rules, especially at the lower altitudes, since all aircraft start and conclude their operations at ground level. A plot of traffic density versus altitude would show the greatest density at traffic pattern altitudes with progressively lower densities at the higher altitudes. In recognition of traffic density trends, GATES Learjet recently certified its Century III models (24E, 24F, 25D, and 25F) for operations at altitudes up to 15,545 m (51,000 ft). These aircraft will literally have the sky to themselves above about 13,716 m (45,000 ft). In this same spirit, general aviation aircraft manufacturers will be building a greater percentage of airplanes capable of routine operations in positive controlled airspace where separation from other aircraft is assured [currently 5486 m (18,000 ft) and above].

General aviation has had a long-standing interest in emulating the scheduled airlines, but there have been obstacles. Besides cost, these have had to do with the size of general aviation airplanes in relation to the size and weight of available instrumentation and avionics. In recent years, the larger corporate jets and turboprops have mastered the emulation goal and the mastery is extending to downsized aircraft. The technology-related pace has been accelerated by turbine engine, avionic, and autopilot developments, and additional progress is foreseen for the decade ahead. The key technology elements will involve small turbine engines in combination with digital, integrated avionics systems. Some of the market applications and corresponding mission profiles identified on the pages that follow reflect expected progress in these areas, both from a technology and a cost standpoint.

CANDIDATE AIRPLANES AND MISSION PROFILES FOR TRADE STUDIES

The established major airframe manufacturers are a very conservative lot, and this is for a good reason. According to James N. Lew, senior vice president (now retired) for engineering of Beech Aircraft, development costs, including production tooling, of a proposed new airplane may range from $4,500 to $6,000 per pound of airframe (1976 dollars), where nonpressurized airframes weigh about 66 percent the empty weight and pressurized airframes average 73 percent of the empty weight of the airplane. Clearly, a large investment is involved, and the manufacturer must be very sure that he has selected the proper engine for the new design, or at least that there is a powerplant alternative should the selected engine prove unsatisfactory. He must also consider product liability when choosing a new engine.

TABLE XII. PERFORMANCE CAPABILITIES OF PISTON AIRCRAFT BEFORE RETROFIT[1] (SI Units)

	AIRPLANE					
	MOONEY 201		COUGAR	AEROSTAR 601P	
Persons on Board	4		4	6	
Gross Weight, kg	1243		1724	2722	
Pressurized	NO		NO	YES	
Engine Rated kW, each	149		119	216	
Takeoff Distance (SL, STD Day, GW)	Short	Normal			
Ground Run, m	271	284	305	395	
Over 15.2 m Obstacle, m	463	540	564	549	
Rate of Climb (SL, STD Day, GW) m/min	312		366	549	
Time to Climb to Indicated Altitude, - Min	25.0 to 4572 m		30 to 4572 m	21.0 to 7620 m	
Maximum Cruise Speed, km/h	324		311	476	
Service Ceiling, m	5700		5578	8534	
Range (45 Min Reserve)					
Altitude, m	2438		2591	4572	7620
Range, km	995		859	1109	1217
Speed, km/h	300		296	428	441
Max Fuel with Full Seats & Bags[2], l	170		284	450	450
km/l	7.72		4.35	3.23	3.78
Seat -km/l	30.9		17.4	19.4	22.7
Landing Distance (SL, STD Day, GW)	Maximum Performance				
Over 15.2 m Obstacle, m	491		488	815	
Ground Roll, m	235		274	302	

[1]From Aircraft Handbook Data
[2]Assumes 90.7 kg for each person on board and their baggage

TABLE XII. PERFORMANCE CAPABILITIES OF PISTON AIRCRAFT BEFORE RETROFIT[1] (English)

	AIRPLANE					
	MOONEY 201		COUGAR	AEROSTAR 601P	
Persons on Board	4		4	6	
Gross Weight, lbm	2,740		3,800	6,000	
Pressurized	NO		NO	YES	
Engine Rated hp, each	200		160	290	
Takeoff Distance (SL, STD Day, GW)	Short	Normal			
Ground Run, ft	890	931	1000	1296	
Over 50 ft Obstacle, ft	1,518	1,771	1,850	1,800	
Rate of Climb (SL, STD Day, GW), ft/min	1,023		1,200	1,800	
Time to Climb to Indicated Altitude, - Min	25.0 to 15,000 ft		30 to 15,000 ft	21.0 to 25,000 ft	
Maximum Cruise Speed, knots	175		168	257	
Service Ceiling, ft	18,700		18,300	28,000	
Range (45 Min Reserve)					
Altitude, ft	8,000		8,500	15,000	25,000
Range, nm	537		464	599	657
Speed, knots	162		160	231	238
Max Fuel with Full Seats & Bags[2], gal	45		75	119	119
nm/gal	15.78		8.89	6.60	7.72
Seat-nm/gal	63.1		35.6	39.6	46.3
Landing Distance (SL, STD Day, GW)	Maximum Performance				
Over 50 ft Obstacle, ft	1,610		1,600	[illegible]	
Ground Roll, ft	770		900	[illegible]	

[1]From Aircraft Handbook Data
[2]Assumes 200 lb for each person on board and their baggage

TABLE XIII. AVERAGE NUMBER OF PERSONS TRAVELING IN GENERAL AVIATION AIRCRAFT (1975 Civil Air Patrol Survey)

Aircraft Type	Average Number Of Travelers (Including Crew)	Crew Requirements
Single-engine piston	2.1	1
Helicopters	2.9	1
Multi-engine piston	3.8	1
Turboprop	5.7	1
Turbojet/turbofan	5.4	2

Because of airframe development cost and product liability considerations, the introductory use of a new turboprop engine would probably be by engine substitution in an existing model. A new turbofan would probably also be introduced in an existing airframe if an appropriate airframe became available by the time of introduction. The re-engined airplanes would have to provide performance or cost advantages (or both) over preceding models.

The candidate fixed-shaft turboprop engine was retrofitted to, and evaluated in, three contemporary piston-powered airplanes. Two of the airplanes were twins and one was a single. One of the twins, the Gulfstream American Cougar, was selected to permit engine merit evaluations at derated powers where the introductory risk could be minimized and in-service experience gained. The other twin, a Piper Aerostar 601P, was chosen for evaluating the merit of nominally-rated engines. The single-engine Mooney 201 was selected to satisfy the need to substitute the turboprop for a four-cylinder piston engine in lieu of a heavier six-cylinder engine. The weight difference between the turboprop and a six-cylinder piston engine produced airplane balance and stability perturbations with attendant retrofit complications.

Mission goals were to provide, at comparable gross weights, equal or better performance and economy of operation in terms of seat-km/l (seat-nm/gal) than the airplane being retrofitted. An expanded airplane operating envelope, together with a 1112-km (600-nm) stage length capability with all seats occupied, was also desired. Table XII lists the performance capabilities of the aircraft being retrofitted (before retrofit), and Figure 5 depicts these aircraft after retrofit. A candidate twin turbofan-powered configuration is also shown in Figure 5.

The twin turbofan airplane was sized to accommodate the average number of travelers shown in Table XIII, i.e., 5.4. Six seats were believed more than adequate, since the requirement for two crew members on all business jets has been relaxed, and because the 5.4 figure provided by the Civil Air Patrol Survey included, according to a private survey, an average of one traveler having no association with the business at hand. This person was traveling simply because extra seating was available that would otherwise go unoccupied. Also, with only six passenger seats, a crew of two would be unlikely for most missions. Only one professional crew member would be used, or the businessman would fly the airplane himself.

The selected mission for the twin turbofan airplane involved a 1112-km (600-nm) range requirement at a Mach 0.6 cruise at 9144 m (30,000 ft). Adequate fuel would be needed to travel to the destination 1112 km (600 nm) away, hold for 45 minutes and then proceed to an alternate destination. Consequently, a 1852 km (1000 nm) range capability with reserves would be desirable.

The Mach 0.6 cruise speed was selected because it falls short of the speed where compressibility influences become significant. Once near the compressibility flight regime, lifting surfaces need to be made thinner and this adversely affects available wing volume for fuel storage, a problem unique to small jets since fuel storage volume is reduced by the scale factor cubed while the thrust requirement reduces by the scale factor squared. Also, the potential for airplane stability and control anomalies begins to influence control system design. To avoid adverse influences from local shockwaves on the lifting surfaces, added control system complexity and cost can be anticipated (e.g. from a Mach trim device that includes actuator, computer, air data sensor, and aural Mach overspeed warning components). The added cost and complexity of Mach trim, a yaw damper, etc., are not believed warranted in small jets that will be flown by nonprofessional pilots.

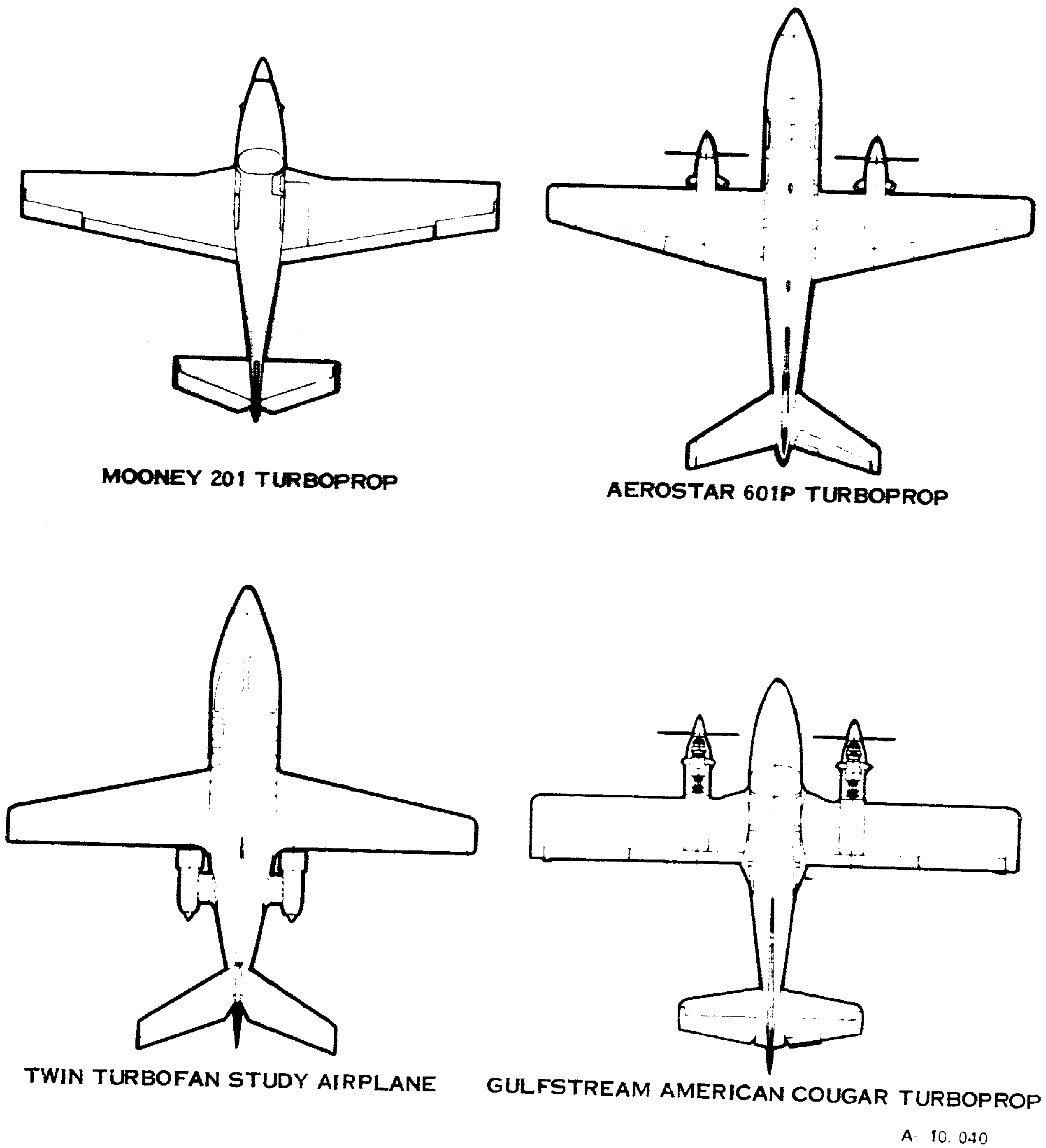

Figure 5. GATE Study Airplanes

SECTION 5

BROAD SCOPE TRADE-OFF STUDIES

Turboprop and turbofan parametric studies for projected 1988 state-of-the-art general aviation turbine engines were conducted using as a basis, data generated during the market analysis. Specifically, the market analysis shows a need for a low-cost, flat-rated turboprop capable of replacing four- and six-cylinder, horizontally-opposed, turbocharged piston engines producing from 134 kW to more than 224 kW (180 hp to more than 300 hp). A significant market for a low-cost, fuel-efficient turbofan in the 4448 N (1,000 lb) thrust class was also foreseen. Both the turboprop and turbofan, when installed in appropriate aircraft, would have to provide performance, fuel economy, and life cycle cost (LCC) benefits comparable to piston airplane counterparts. Attendant safety, utility, and environmental improvements are additional prerequisites.

The trade studies described in this section provide examples of work that was done to define candidate turboprop (T/P), turboshaft (T/S), and turbofan (T/F) engine concepts and layouts for consideration relative to common core compatibility.

TURBOPROP/TURBOSHAFT

Parametric Study

Parametric performance data for shaft engine cycles was calculated using compressor and turbine efficiency, compressor temperature rise, and turbine inlet temperature (TIT) as variables. The data was prepared for flight speeds and altitudes which were determined representative of operational conditions expected for the T/P airplanes defined in the marketing study, i.e., SL/Mach 0, 4572 m (15,000 ft)/Mach 0.3, and 7620 m (25,000 ft)/Mach 0.3.

Samples of the parametric performance data generated during the T/P design point study are shown in Figures 6 and 7. The curves show relationships between specific fuel consumption (SFC) and specific power at seven compressor temperature-rise values between 167°K and 500°K (300°F and 900°F) and five turbine inlet temperatures between 1144°K and 1589°K (1600°F and 2400°F). To illustrate the effect of component efficiency on specific performance, additional plots were prepared for compressor and turbine efficiency values incremented by four percentage points in plus and minus directions from nominal values ($\eta_c = 0.78$, $\eta_t = 0.86$), Figures 8 and 9. These curves, for a 1367°K (2000°F) TIT case, illustrate the importance of aerodynamic component development for SFC and specific performance gains. A four percentage point improvement in compressor and turbine efficiency (Figure 8), for example, can produce an SFC reduction of 18 percent. Potential improvements of this order emphasize the necessity for working to maximize efficiencies for viability in a low-cost T/P propulsion unit.

Turboprop Design Point Choice Rationale

The choice of the optimum design point of a turbine engine is a compromise involving numerous variables. Some, such as performance, can be thoroughly quantified at the early stages of design; and others, such as costs and mechanical refinements, are less easily quantified. The process of cycle selection involves, in general, a combination of design point analysis focused around a preliminary design concept

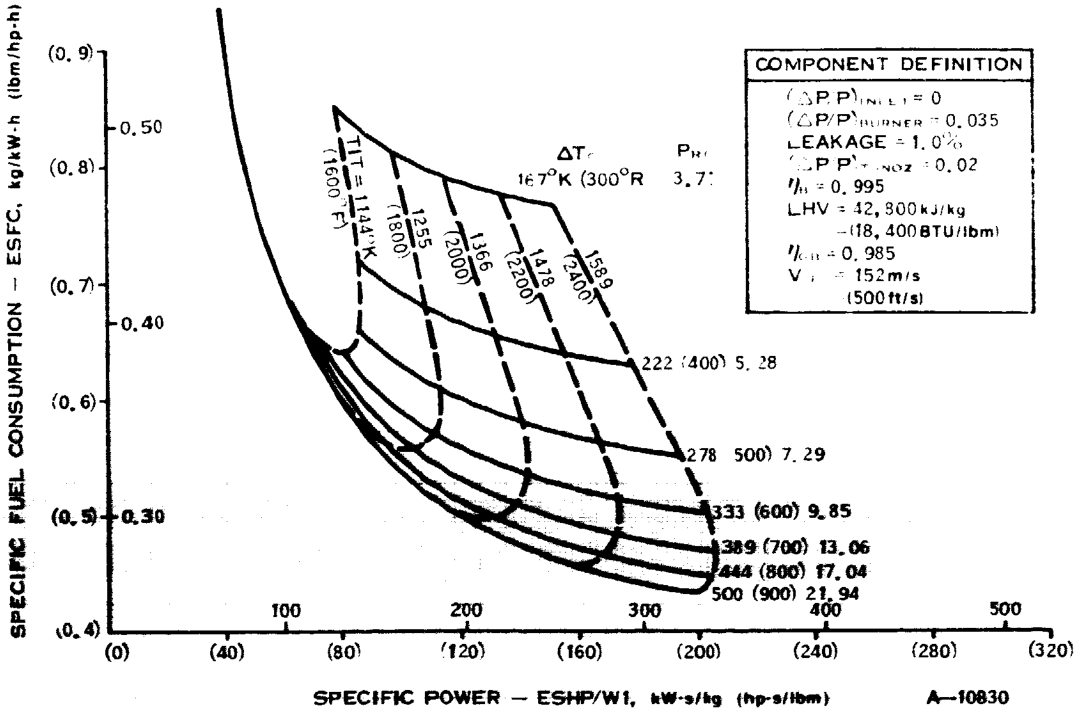

Figure 6. Turboprop Parametric Design Point Study - SL/Mach 0, STD Day, η_c = 0.78, η_t = 0.82

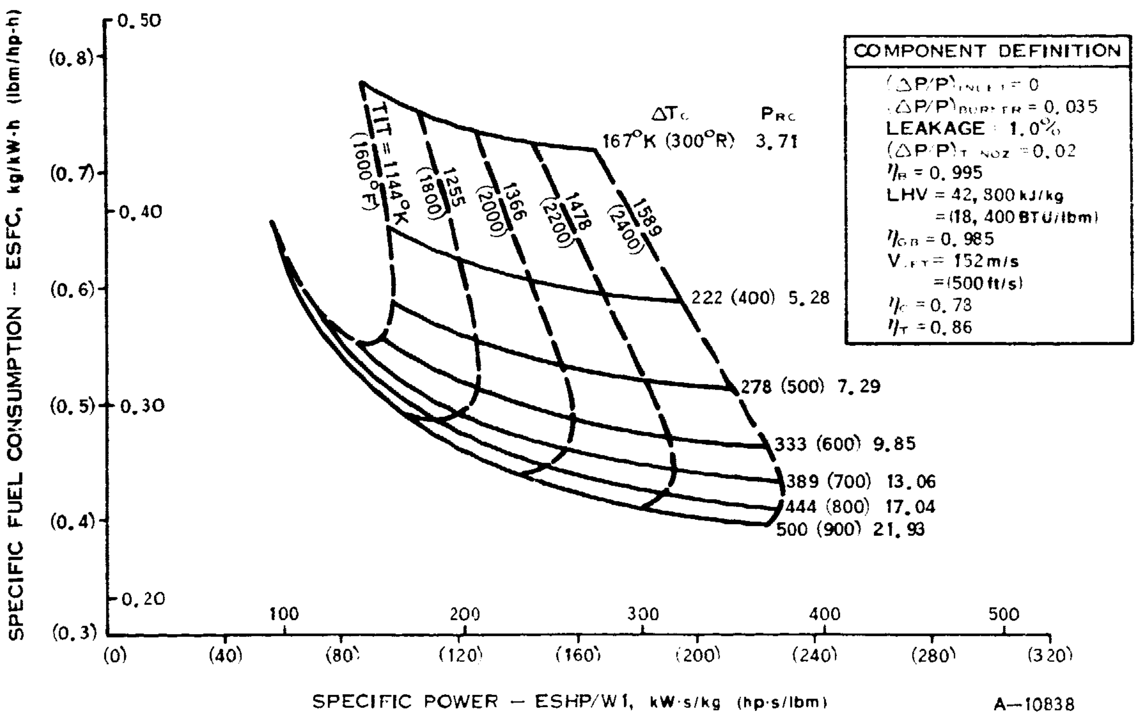

Figure 7. Turboprop Parametric Design Point Study - SL/Mach 0, STD Day, η_c = 0.78, η_t = 0.86

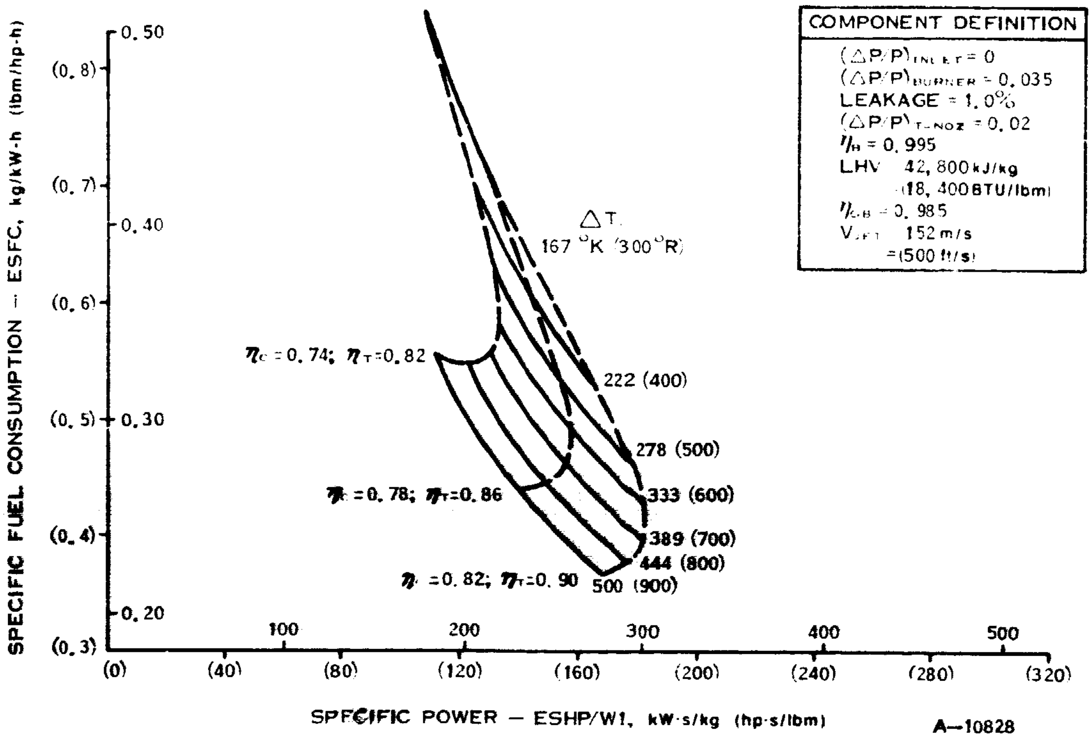

Figure 8. Turboprop Parmetric Design Point Study - SL/Mach 0, STD Day, TIT = 1366°K (2000°F)

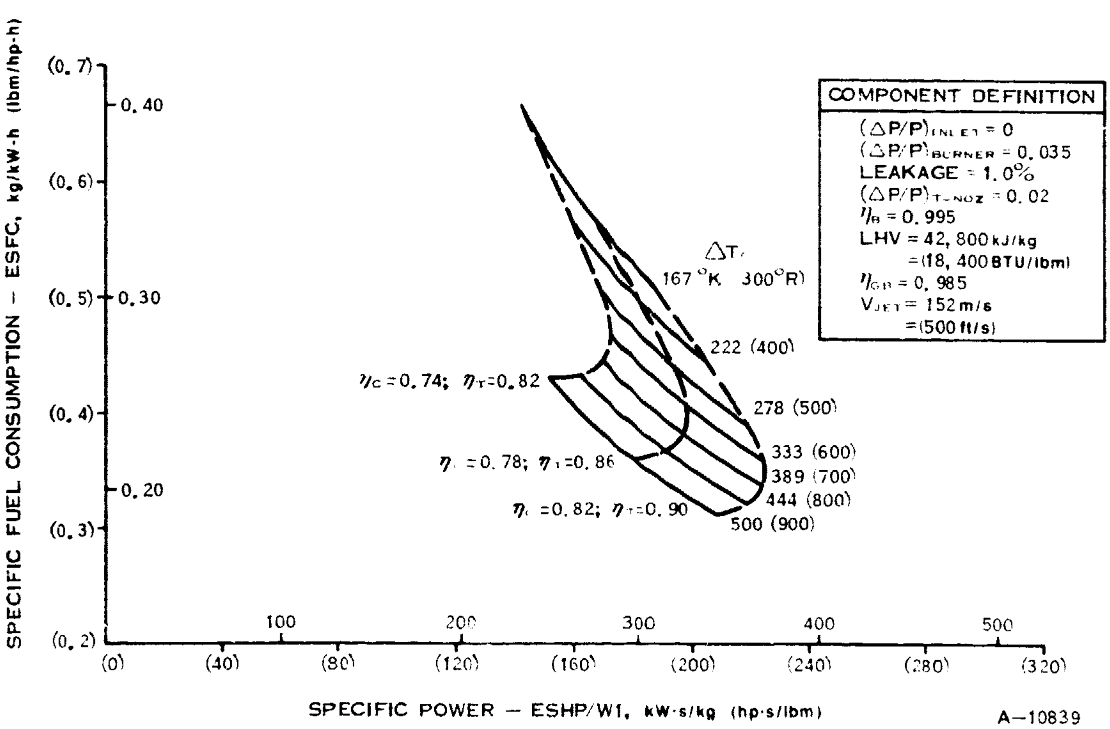

Figure 9. Turboprop Parametric Design Point Study - 7620 m (25,000 ft)/Mach 0.3, STD Day, TIT = 1366°K (2000°F)

together with a great deal of judgment in interpreting the impact of cycle parameters. In the case of GATE powerplants, previous studies of turbine engines utilizing low cost manufacturing techniques based on low rotational speeds indicated that substantial cost benefits can be accrued if reasonable performance can be obtained from aerodynamically simplified components. These components will, of course, have to be compatible with mechanical arrangements having good dynamic characteristics.

The performance characteristics of a simplified-geometry axial compressor were quantified and shown as a function of pressure ratio, as indicated in Figure 10. Notice that these data indicate that at pressure ratios over 3.9:1 some form of stability control device might be necessary. Test performance of a sample compressor of this type of construction indicated that such a requirement might indeed be real. The taking of bleed air for cabin pressurization from the axial compressor might obviate the need for a separate, engine-mounted stability control device, however.

The performance of a low cost, geometry-limited, centrifugal compressor which would be compatible with a "low cost axial" was quantified as a function of its pressure ratio and the pressure ratio of the leading compressor element at constant absolute flow. This information, shown in Figure 11, indicates that a severe performance penalty might occur if the axial compressor element produces a pressure ratio exceeding 4:1. Combined compressor performance was then estimated and is shown in Figure 12. These data indicate that lead compressor pressure ratios between 3:1 and 4:1 do not significantly change overall compressor performance, but a lead compressor element having a 5:1 pressure ratio will significantly degrade component performance.

To utilize this information in assessing the merits of a compressor, a preliminary estimate of the probable cruise turbine inlet temperature range must be made. Cruise turbine inlet temperatures of 1200°K (1700°F) and 1255°K (1800°F) were chosen because it is believed that a low cost turbine design which has desirable life characteristics and utilizes semi-noncritical materials will be limited to the 1255°K (1800°F) cruise temperature level.

With the decision to use these turbine temperatures, stage turbine efficiencies of 86 percent for a four stage turbine were estimated and trade studies of specific fuel consumption versus pressure ratio were made. The resulting parametric performance, evaluated at 74 percent compressor efficiency and the selected turbine inlet temperatures, is shown in Figure 13 for the 7620 m (25,000 ft), 0.3 Mach number turboprop airplane flight condition. Superimposed on these data is the performance of the engine concept with compressor efficiency adjusted for overall pressure ratio as shown in the 3:1 and 4:1 lead compressor configuration data of Figure 12. This information shows that specific fuel consumption will be a minimum at a 15:1 pressure ratio at this condition. However, with a penalty of less than two percent in specific fuel consumption, a pressure ratio as low as 11:1 can be used, particularly if cost benefits are to be obtained. From this trade study, it was concluded that a compressor of approximately 10:1 pressure ratio at sea level static conditions is optimum. Significant increases of pressure ratio over 10:1 will not be advantageous as long as the cruise turbine temperatures are held within the 1200°K (1700°F) to 1255°K (1800°F) range because compressor related engine costs will escalate with increasing pressure ratio.

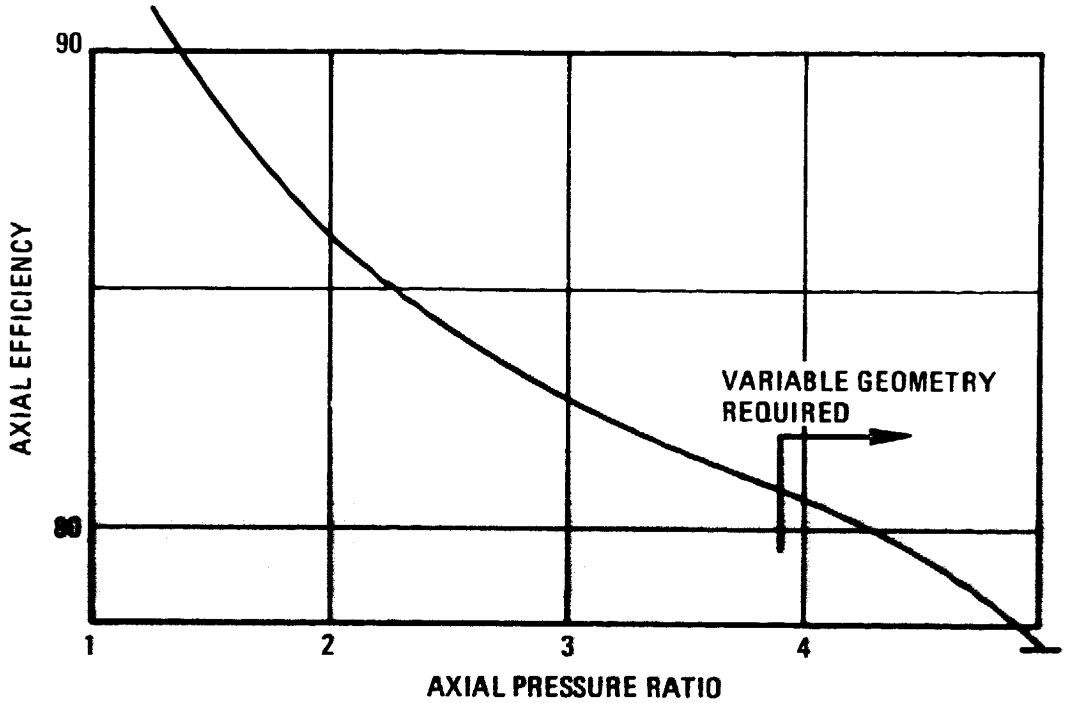

Figure 10. Effect of Axial Pressure Ratio on Axial Efficiency for a Geometrically Constrained Compressor (Nominal Development)

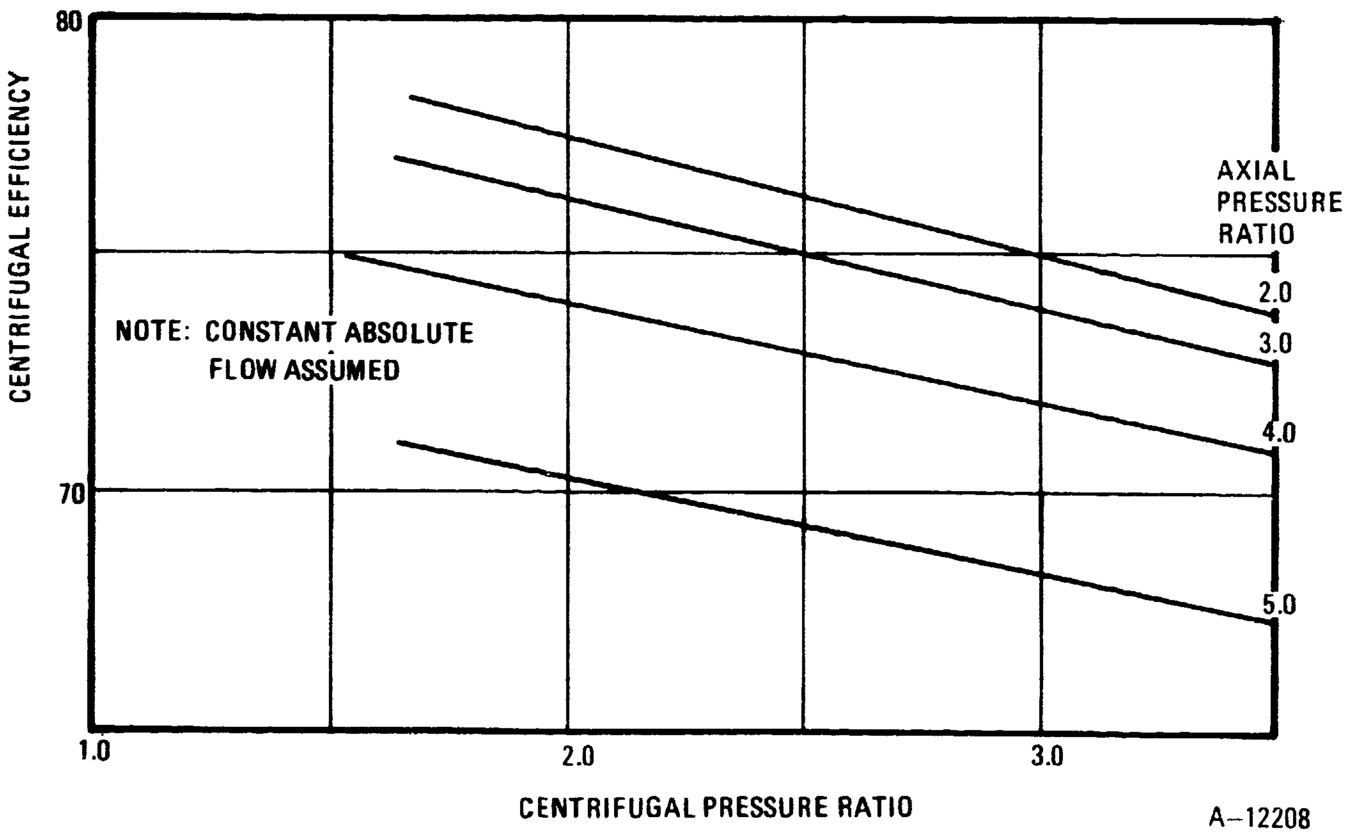

Figure 11. Effect of Axial and Centrifugal Pressure Ratios on the Efficiency of a Low Specific Speed, Axial-Fed Centrifugal Compressor

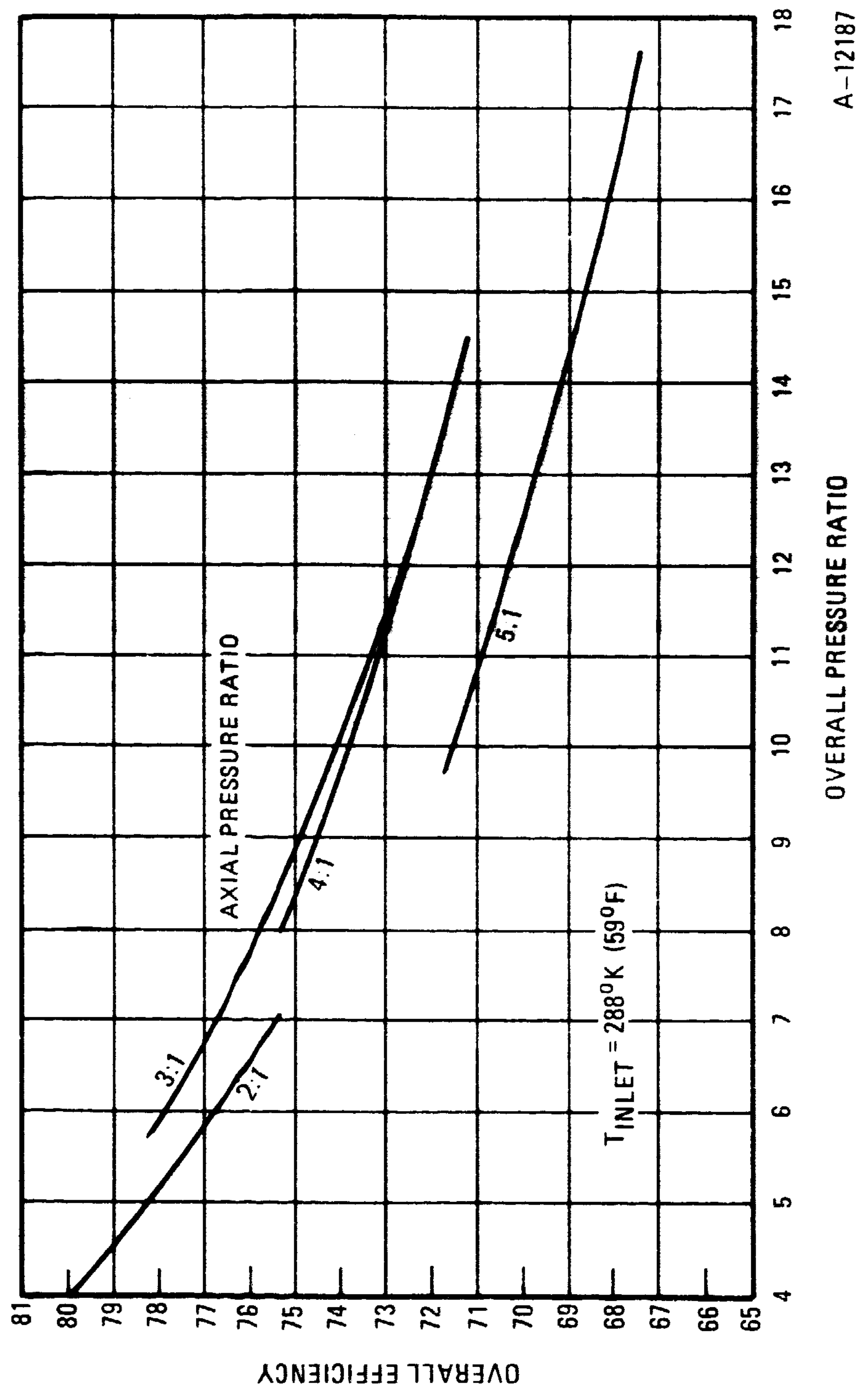

Figure 12. Effect of Overall Pressure Ratio and Axial Pressure Ratio on the Overall Efficiency of a Combined Axial Centrifugal Compressor

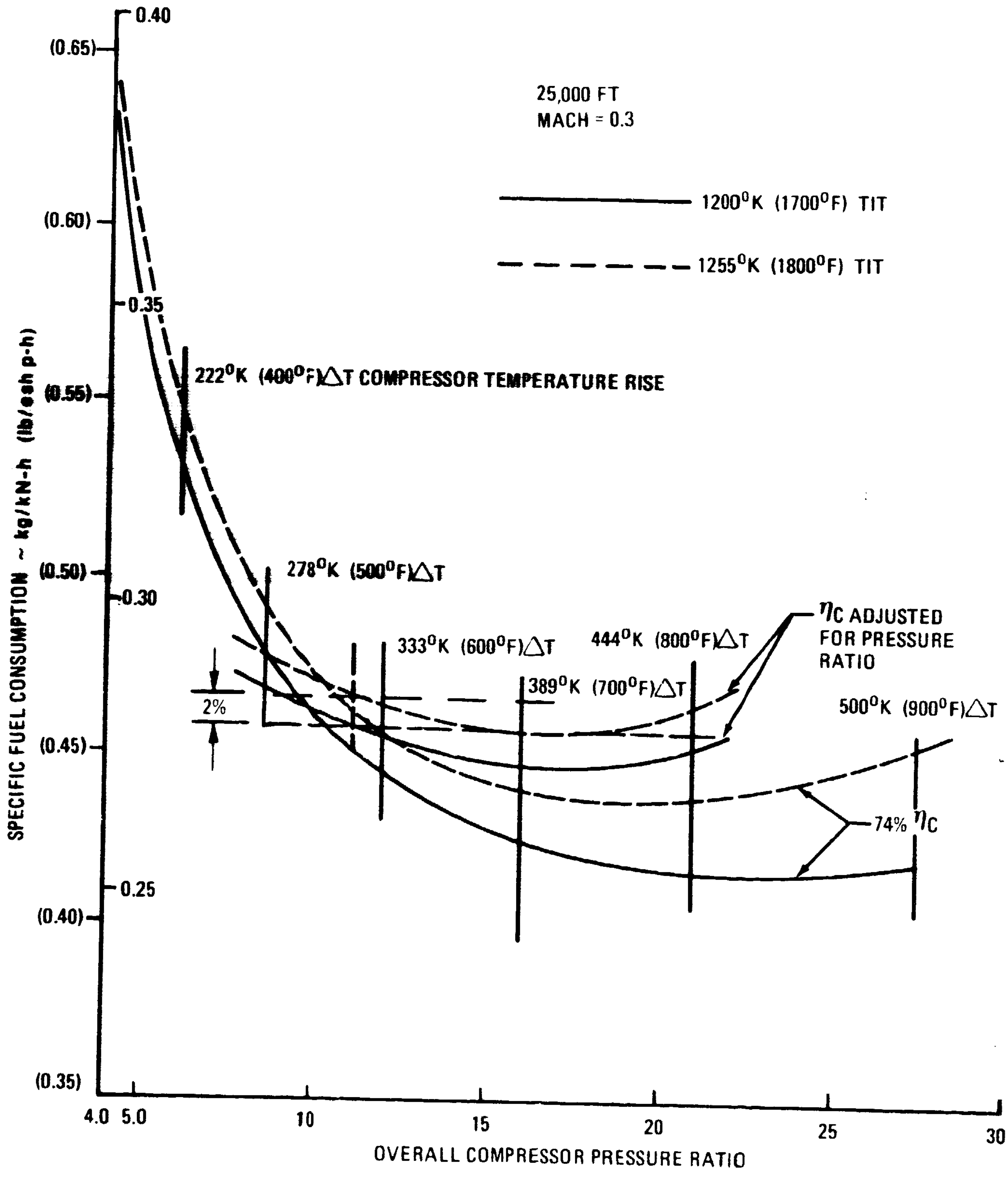

Figure 13. Turboprop Performance - Specific Fuel Consumption vs Compressor Pressure Ratio at 86% Turbine Stage Efficiency 25,000 ft 0.3 Mach Number

The low cost fabrication concept proposed for this engine introduces anomalies into the conventional understanding of costs. This is because of the minor influence of pressure ratio and the number of stages on actual compressor cost. A higher pressure ratio compressor requires a larger number of turbine stages, however, to properly expand the gas and this in turn requires a longer shaft system. The length extension introduces cost increases into the shaft and shaft suspension in increments which are functions of the particular mechanical design concept.

Figure 14 shows the effect of the choice of the number of axial stages when combined with a low specific speed centrifugal of approximately 167°K (300°F) temperature rise at different temperature rises per axial stage. Experience has shown that the limitation of axial stage temperature rise to 28°K (50°F) per stage permits low cost fabrication methods to be used, and the limitation of the number of stages to six increases the probability of eliminating stability control devices. **Since a six-stage simplified low cost axial is less expensive than an axial of fewer stages at higher pressure ratio and will run at considerably lower rotational speeds and stresses, it was decided that the turboprop compressor design would be a six-stage simplified axial of approximately 167°K (300°F) temperature rise followed by a low specific speed, close-coupled, centrifugal compressor of slightly less than 167°K (300°F) temperature rise.**

Turboprop P7757

After completing the T/P parametric analyses, conceptual layouts were made of candidate T/P engines, and engine performance, weight, and cost trade-offs were made. The surviving concept was configured for good performance and minimum development and procurement costs. It uses an axial/centrifugal type compressor with the axial component based on low-cost design and manufacturing concepts developed for the WR33 low-cost turbojet. The turbine concept is based on manufacturing techniques proprietary to Williams Research Corporation (WRC) for low-cost rotor and stator construction. These techniques result in manufacturing costs which characteristically are relatively independent of the number of stages in the component. For satisfactory results, a low stress level design or low specific speed component is required that uses low-speed aerodynamics.

The goal of a long operating life led to a time between overhaul (TBO) design objective of matching airframe life (arbitrarily assumed to be 10,000 hours). If the objective is achieved, a user of the turboprop would no longer have to set aside a reserve for overhaul or engine exchange allowance (typically \$5 to \$10 per flight-hour for piston engines) in his direct operating cost accounting. The impact on airplane and engine LCC would be remarkable.

The engine size selected would allow for a flat rating of approximately 224 kW to about 6069 m (300 hp to about 20,000 ft) altitude and the specific performance level would be better than competitive piston engines when proper allowances are made for the lighter weight [typically a 45 to 181 kg (100 to 400 lbm) advantage], reduced cooling drag (piston engine cooling drag is 5 to 20 percent of the total cruise drag of the airplane) and the lesser frontal area.

The recommended engine configuration is characterized by a six-stage, low-speed axial compressor followed by a low specific speed centrifugal compressor which supplies air to a shaft nozzle-fed combustor. A four-stage axial turbine is driven by combustor efflux. The core engine is reversed, with the propeller drive gearbox

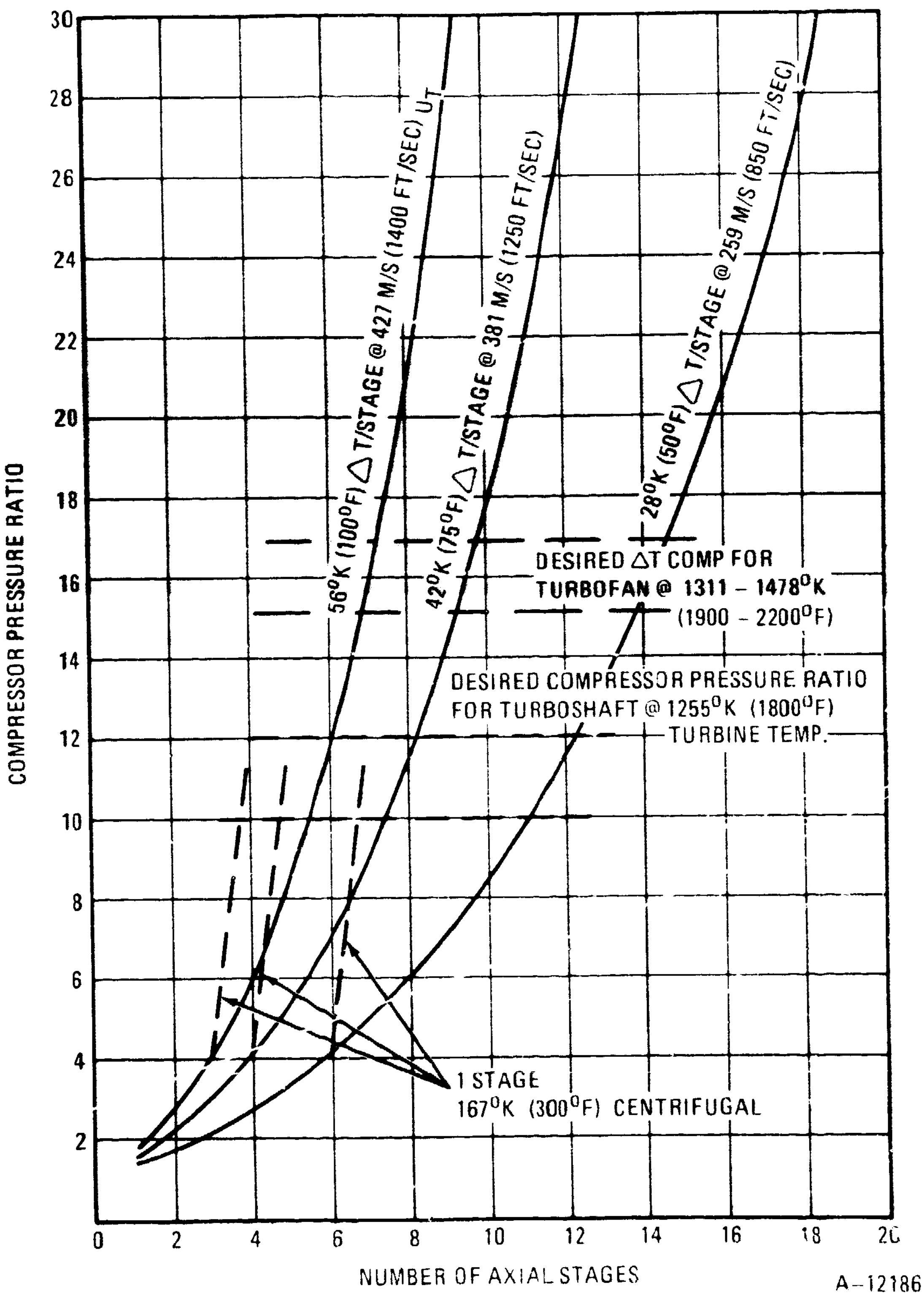

Figure 14. Compressor Pressure Ratio versus Number of Axial Stages for Various Work-Level Stages of Compression

mounted on the turbine end of the shaft system and the compressor inlet at the aft end of the engine. The exhaust is discharged from two ports on either side of the engine and turned aft to recover as much residual thrust as possible. The dual exhausts are to balance side forces, thereby precluding exhaust contributions to possible airplane spin recovery problems.

The compressor pressure ratio is over 10:1, and with conservative efficiencies the turboprop could provide an 8 or 9 percent fuel efficiency advantage over competing piston engines. A 25 percent installed fuel efficiency advantage could be obtained through an aircraft specifically configured to capitalize on the lighter, more compact, turbine power unit and through more extensive engine development. Figure 15 is an installation drawing for the fixed shaft P-7757 turboprop. Estimated component performance is shown in Table XIV. Figures 16, 17 and 18 show some of the engine performance data that were used in conjunction with the NASA-developed General Aviation Synthesis Program (GASP) to predict the performance of Piper, Gulfstream American, and Mooney aircraft retrofitted with the turboprop.

Airplane Studies

Three existing airplanes were chosen for study relative to T/P retrofit possibilities. Two of these were twins and one was a single. The twins were a Gulfstream American Cougar and a Piper Aerostar 601P. The single was a Mooney 201. Other airplanes could have been selected for study and some would have shown the turboprop in a better light from the fuel efficiency standpoint vis-á-vis the piston than did the Cougar and Mooney. Nevertheless, the selections were made according to the following rationale.

At the time the airplane studies were initiated, only a cursory T/P cost analysis had been made. This analysis indicated that the turboprop could be produced for an OEM price falling in the the $10,000 to $30,000 range. Because the cost was influenced by production rate and quantity, and quantity, in turn, by the types of airplane capable of productively using the engine, a twin and a single at the lower end of the retractable gear airplane cost spectrum were selected for analysis. If these could be shown to benefit from a turbine engine retrofit, the potential for the engine would be very great indeed. Thus, the Mooney and Cougar were selected as representative of the type of airplane that could have a decided influence on the demand for the turboprop and the resultant cost. The more expensive Aerostar was selected as one of the more appropriate airplanes for retrofit from the standpoint of demonstrating fuel efficiency and LCC advantages.

There were other reasons for selecting the Cougar and Mooney. The four-place Cougar, for example, would be an excellent test bed for engine introduction, because it is a twin and very good performance can be achieved at a conservative introductory engine kW (hp) rating. Service experience could thus be obtained with a minimum of risk at an engine life meeting customer expectations. Also, the very large Cougar cabin could easily accommodate two additional passenger seats, and the potential for gross weight growth is excellent. Note, however, that the Cougar is limited with respect to cabin pressurization potential [differential limit about 21 kPa (3 psi)] because of the fuselage shape and structural makeup.

The single-engine Mooney was selected for analysis for several reasons. First, the aerodynamic drag was well known because of the very excellent drag reduction program that preceded the introduction of the Model 201. This facilitated piston airplane performance-matching using GASP and the later turboprop airplane perfor-

TABLE XIV. TURBOPROP P7757 COMPONENT PERFORMANCE SUMMARY (SHEET 1 OF 2)
(SI Units)

	Takeoff		Cruise	
Altitude - m	0	0	4572	4572
Flight Velocity - km/h	0	0	519	519
Ambient Temperature - ^oK	288	288	258	258
Shaft Output Power - kW	228.8	280.1	203.2	241.8
Net Thrust - N	343.9	356.3	134.7	150.8
Fuel Flow - kg/h	91.6	102.6	67.5	77.1
Turbine Inlet Temperature - ^oK	1200	1283	1200	1283
Shaft Speed - rpm	35000	35000	35000	35000
Exhaust Gas Temperature - ^oK	766	824	739	796
BSFC - kg/kW-h	0.400	0.366	0.332	0.319
ESFC - kg/kW-h	0.364	0.338	0.294	0.286
INLET DUCT:				
$\Delta P_t/P_t$	0	0	0	0
AXIAL COMPRESSOR:				
$(W\sqrt{T_t}/P_t)_{in}$ - (kg/s) $\sqrt{^oK}$/kPa	0.271	0.265	0.292	0.287
P_r	3.815	3.854	4.074	4.133
η_c	0.810	0.802	0.810	0.810
CENTRIFUGAL COMPRESSOR:				
$(W\sqrt{T_t}/P_t)_{in}$ - (kg/s) $\sqrt{^oK}$/kPa	0.088	0.087	0.091	0.088
P_r	2.67	2.68	2.79	2.80
η_c	0.726	0.731	0.726	0.730
BURNER:				
$\Delta P_t/P_t$	0.03	0.03	0.03	0.03
ηB @ hf = 42800 kJ/kg	0.99	0.99	0 99	0.99
F/A	0.016	0.018	0.016	0.019

TABLE XIV. ENGINE P7757 COMPONENT PERFORMANCE SUMMARY* (SHEET 2 of 2)
(SI Units)

	Takeoff		Cruise	
FIRST STAGE TURBINE:				
$(W\sqrt{T_t}/P_t)_{in}$ - (kg/s) $\sqrt{^{o}K}$/kPa	0.057	0.057	0.057	0.057
P_b	1.60	1.59	1.60	1.59
η_t	0.860	0.858	0.860	0.859
SECOND STAGE TURBINE:				
$(W\sqrt{T_t}/P_t)_{in}$ - (kg/s) $\sqrt{^{o}K}$/kPa	0.049	0.049	0.087	0.087
P_r	1.66	1.66	1.67	1.67
η_t	0.860	0.859	0.860	0.859
THIRD STAGE TURBINE:				
$(W\sqrt{T_t}/P_t)_{in}$ - (kg/s) $\sqrt{^{o}K}$/kPa	0.136	0.136	0.136	0.136
P_r	1.74	1.74	1.78	1.78
η_t	0.860	0.859	0.860	0.859
FOURTH STAGE TURBINE:				
$(W\sqrt{T_t}/P_t)_{in}$ - (kg/s) $\sqrt{^{o}K}$/kPa	0.224	0.224	0.229	0.229
P_r	1.82	1.84	2.17	2.17
η_t	0.860	0.859	0.855	0.850
EXHAUST DUCT:				
$\Delta P_t/P_t$	0.052	0.054	0.070	0.073
NOZZLE:				
A - cm^2	64.376	64.376	64.376	64.376
P_r	1.110	1.119	1.100	1.130
CF	0.985	0.985	0.985	0.985

*Assumed losses - 1.5% gearbox, 1.119 kW parasitic.

TABLE XIV. TURBOPROP P7757 COMPONENT PERFORMANCE SUMMARY (SHEET 1 OF 2) (English)

	Takeoff		Cruise	
Altitude - ft	0	0	15,000	15,000
Flight Velocity - knots	0	0	280	280
Ambient Temperature - ^{o}F	59	59	5.5	5.5
Shaft Output Power - hp	306.8	375.7	272.5	324.3
Net Thrust - lb	77.3	80.1	30.3	33.9
Fuel Flow - lb/hr	202.0	226.1	148.9	170.0
Turbine Inlet Temperature - ^{o}F	1,700	1,850	1,700	1,850
Shaft Speed - rpm	35,000	35,000	35,000	35,000
Exhaust Gas Temperature - ^{o}F	920	1,024	871	974
BSFC - lb/(hp-hr)	0.658	0.602	0.546	0.524
ESFC - lb/(hp-hr)	0.598	0.555	0.488	0.471
INLET DUCT:				
$\Delta P_t/P_t$	0	0	0	0
AXIAL COMPRESSOR:				
$(W\sqrt{T_t}/P_t)_{in}$ - (lbm/s) $\sqrt{^{o}R}$/psia	5.519	5.402	5.950	5.860
P_r	3.815	3.854	4.074	4.133
η_c	0.810	0.802	0.810	0.810
CENTRIFUGAL COMPRESSOR:				
$(W\sqrt{T_t}/P_t)_{in}$ - (lbm/s) $\sqrt{^{o}R}$/psia	1.81	1.77	1.85	1.80
P_r	2.67	2.68	2.79	2.80
η_c	0.726	0.731	0.726	0.730
BURNER:				
$\Delta P_t/P_t$	0.03	0.03	0.03	0.03
ηB @ hf = 18,400 Btu/lb	0.99	0.99	0.99	0.99
F/A	0.016	0.018	0.016	0.019

TABLE XIV. ENGINE P7757 COMPONENT PERFORMANCE SUMMARY* (SHEET 2 OF 2)
(English)

	Takeoff		Cruise	
FIRST STAGE TURBINE:				
$(W\sqrt{T_t}/P_t)_{in}$ - (lbm/s) $\sqrt{^{o}R}$/psia	1.16	1.16	1.16	1.16
P_b	1.60	1.59	1.60	1.59
η_t	0.860	0.858	0.860	0.859
SECOND STAGE TURBINE:				
$(W\sqrt{T_t}/P_t)_{in}$ - (lbm/s) $\sqrt{^{o}R}$/psia	1.76	1.76	1.77	1.77
P_r	1.66	1.66	1.67	1.67
η_t	0.860	0.859	0.860	0.859
THIRD STAGE TURBINE:				
$(W\sqrt{T_t}/P_t)_{in}$ - (lbm/s) $\sqrt{^{o}R}$/psia	2.78	2.78	2.79	2.79
P_r	1.74	1.74	1.78	1.78
η_t	0.860	0.859	0.860	0.859
FOURTH STAGE TURBINE:				
$(W\sqrt{T_t}/P_t)_{in}$ - (lbm/s) $\sqrt{^{o}R}$/psia	4.56	4.57	4.67	4.68
P_r	1.82	1.84	2.17	2.17
η_t	0.860	0.859	0.855	0.850
EXHAUST DUCT:				
$\Delta P_t/P_t$	0.052	0.054	0.070	0.073
NOZZLE:				
A - in^2	25.345	24.345	24.345	24.345
P_r	1.110	1.119	1.100	1.130
CF	0.985	0.985	0.985	0.985

*Assumed losses - 1.5% gearbox, 1.5 hp parasitic.

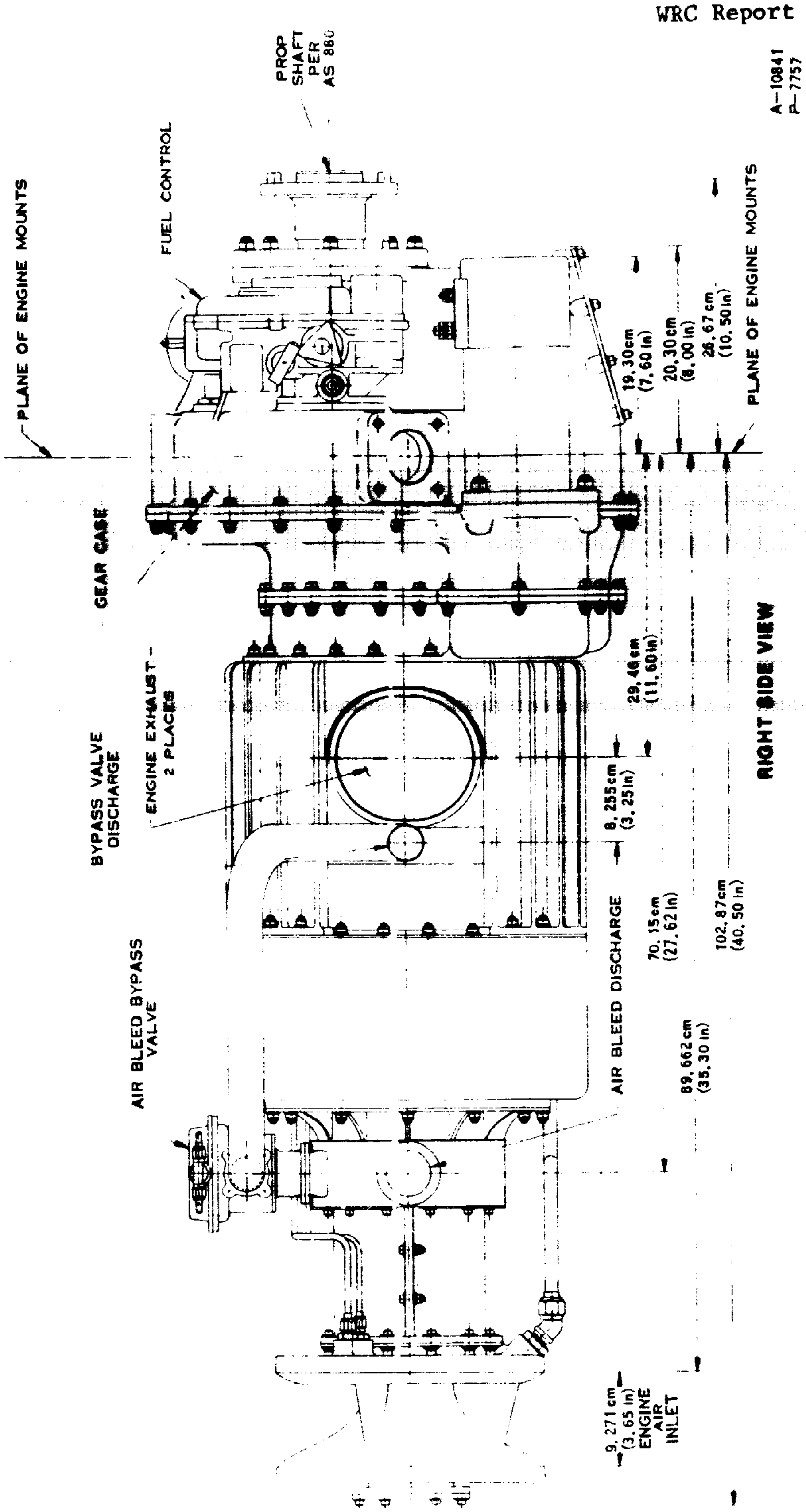

Figure 15. Fixed Shaft Turboprop Installation Drawing (Sheet 1 of 2)

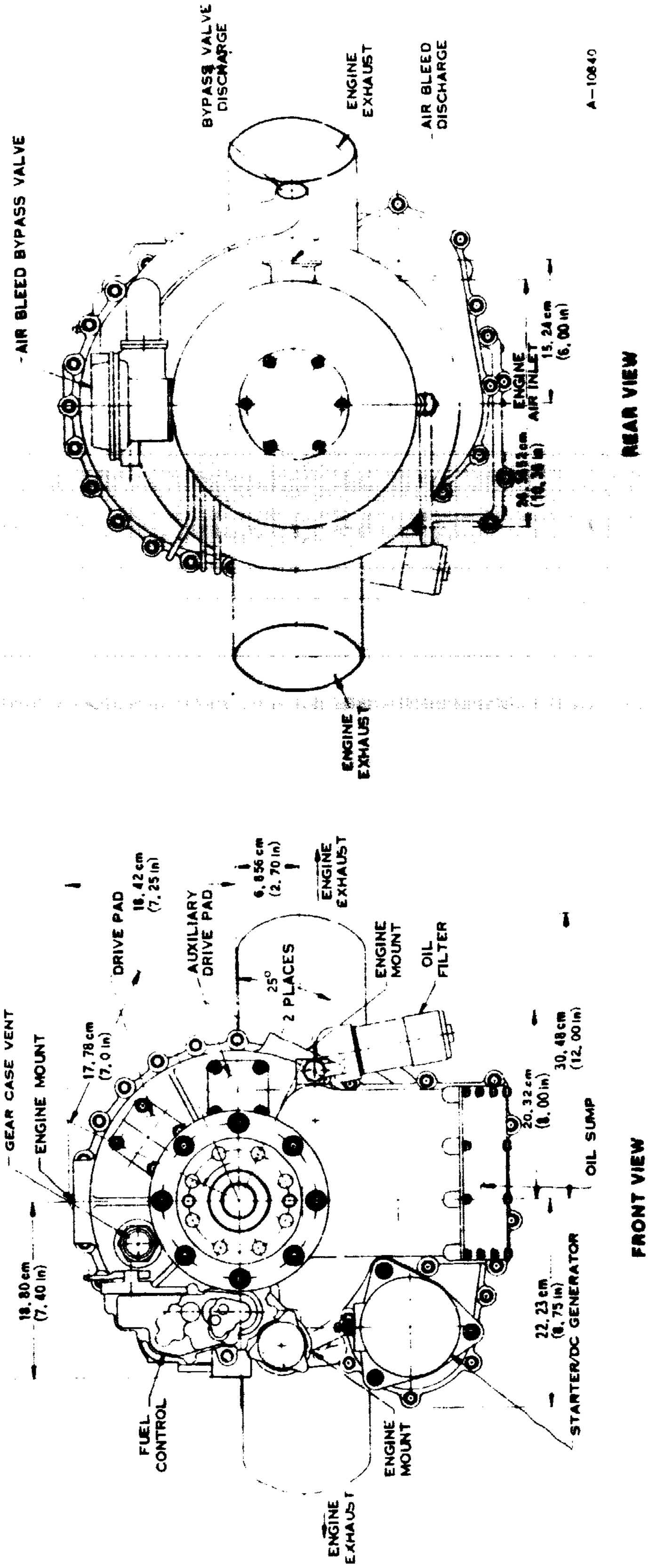

Figure 15. Fixed Shaft Turboprop Installation Drawing (Sheet 2 of 2)

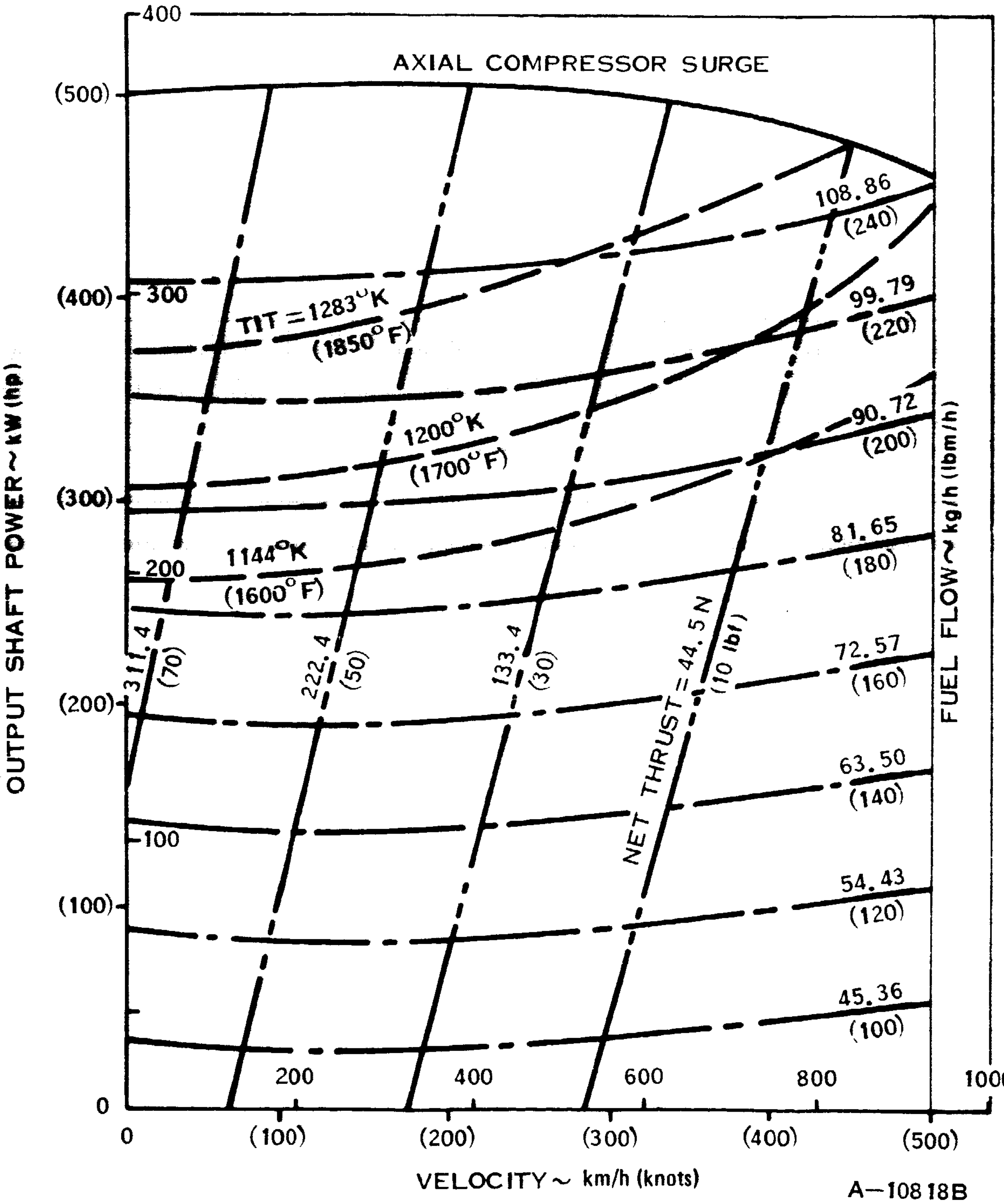

Figure 16. Estimated Performance, Low Cost Turboprop - SL/Standard Day

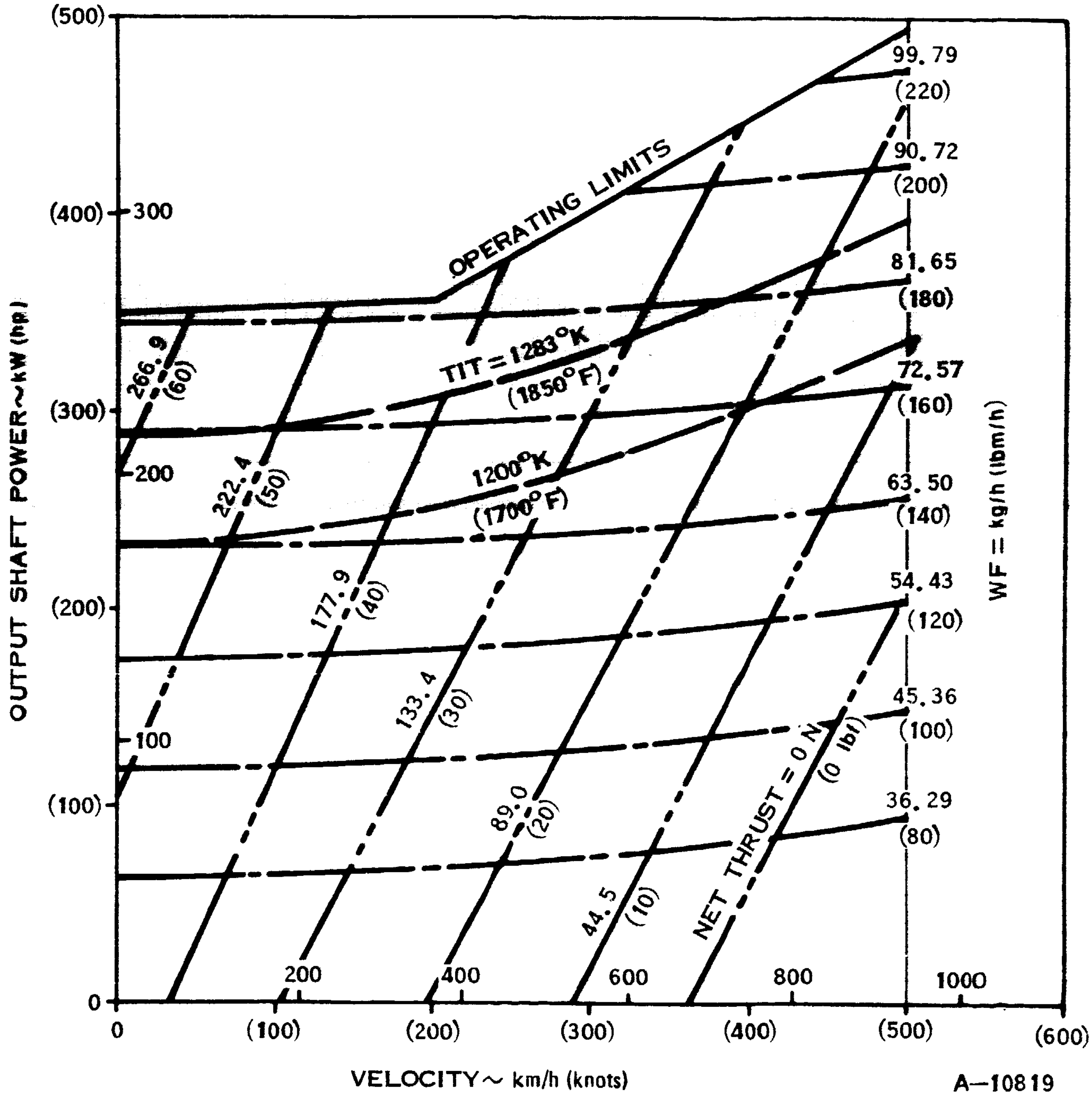

Figure 17. Estimated Performance, Low Cost Turboprop - 4572m (15,000 ft)/ Standard Day

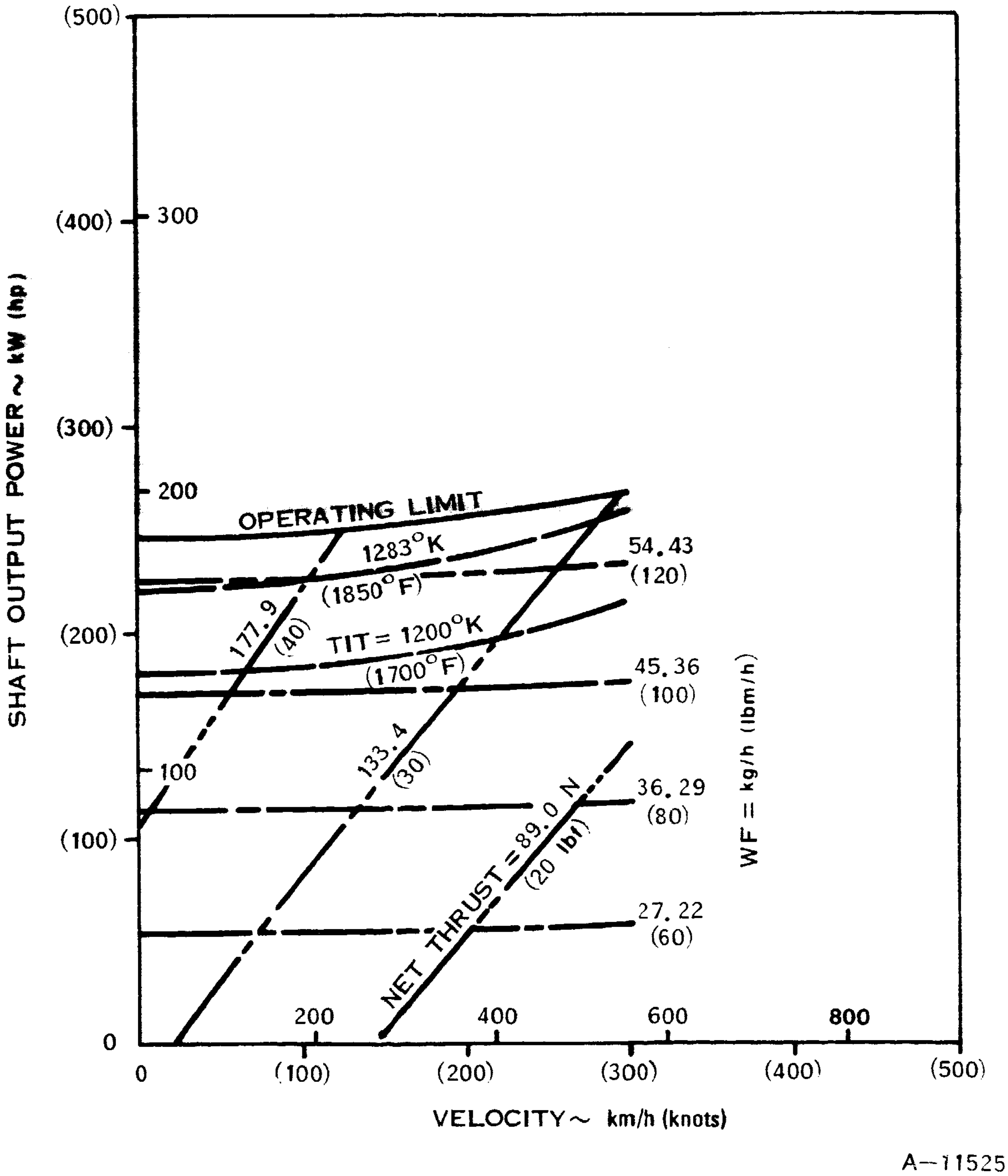

Figure 18. Estimated Performance, Low Cost Turboprop - 7620m (25,000 ft) Standard Day

mance predictions. Secondly, the Mooney structure has proven to be rugged, and a high diving speed has been demonstrated. The airframe is therefore well suited for a higher kW (hp) application. Thirdly, the lightweight turboprop can be more easily substituted for a four-cylinder piston engine such as the Model 201's Lycoming IO-360-A3B6D than for a six-cylinder piston engine. Substitution for the six-cylinder engine requires a much longer nose section for balance and this perturbs airplane stability. While this is certainly not an insurmountable obstacle, the work involved would have limited the extent of analyses of other airplanes during the trade studies. Finally, a potential exists for pressurizing the compact Model 201 cabin.

Prior to initiating performance analyses involving piston and turboprop-powered versions of the Aerostar, Cougar, and Mooney, three-view drawings of each airplane were obtained from the respective manufacturers together with aerodynamic and weights data. Aerostar and Mooney FAA-approved flight manual data were also acquired. Cougar flight manual data was unavailable at the time.

Three-view drawings of the turboprop-powered version of each airplane were generated by modifying the piston airplane drawings as shown in Figures 19, 20, and 21. Twin-engine airplane piston/turboprop nacelle comparison drawings were also generated (Figures 22 and 23) to illustrate the much more compact and streamlined turboprop engine nacelles. The three-view drawings, aerodynamic data, and the weights information were then used to develop input data lists for the GASP program.

The initial GASP runs involved the piston-powered Mooney and Aerostar airplanes and attempts to match airplane performance data published in the flight manuals. After several iterations during which input adjustments were made, a suitable performance match was achieved for each airplane; i.e., takeoff distance, climb rate, maximum speed, and landing distance were matched.

T/P engine data were then inserted in GASP together with input changes to account for powerplant, propeller, pressurization, and aerodynamic differences. Gross weights of the retrofitted Aerostar and Mooney were held to the piston airplane values. Because the retrofitted Cougar was overpowered at the piston airplane's gross weight, two seats were added and the gross weight increased by 408 kg (900 lbm). Each turboprop-powered airplane, at gross weight, carried substantially more fuel than the piston counterpart when payload was held constant (see Tables XVI and XX).

Results of the GASP computer runs are shown in Tables XV thru XXI for the Aerostar, Cougar, and Mooney, respectively. Note in Table XV that the turboprop-powered Aerostar takeoff is shorter, climb rate faster, ceiling higher, and cruising range substantially greater. Its fuel efficiency at altitudes above 4572 m (15,000 ft) is improved. At 7620 m (25,000 ft) the gain is about 15 percent and at 10668 m (35,000 ft) it is about 40 percent better then the piston at optimum cruising altitude.

Cougar performance, too, is greatly enhanced by the turboprop retrofit. In fact, the conversion transforms the airplane into a wholly new performance class as shown by Table XVIII. Note the 250 percent increase in climb rate and 44 percent improvement in seat-km/l (seat-nm/gal). Engine-out climb rate and single engine ceiling (not shown) are also decidedly higher with obvious safety benefits.

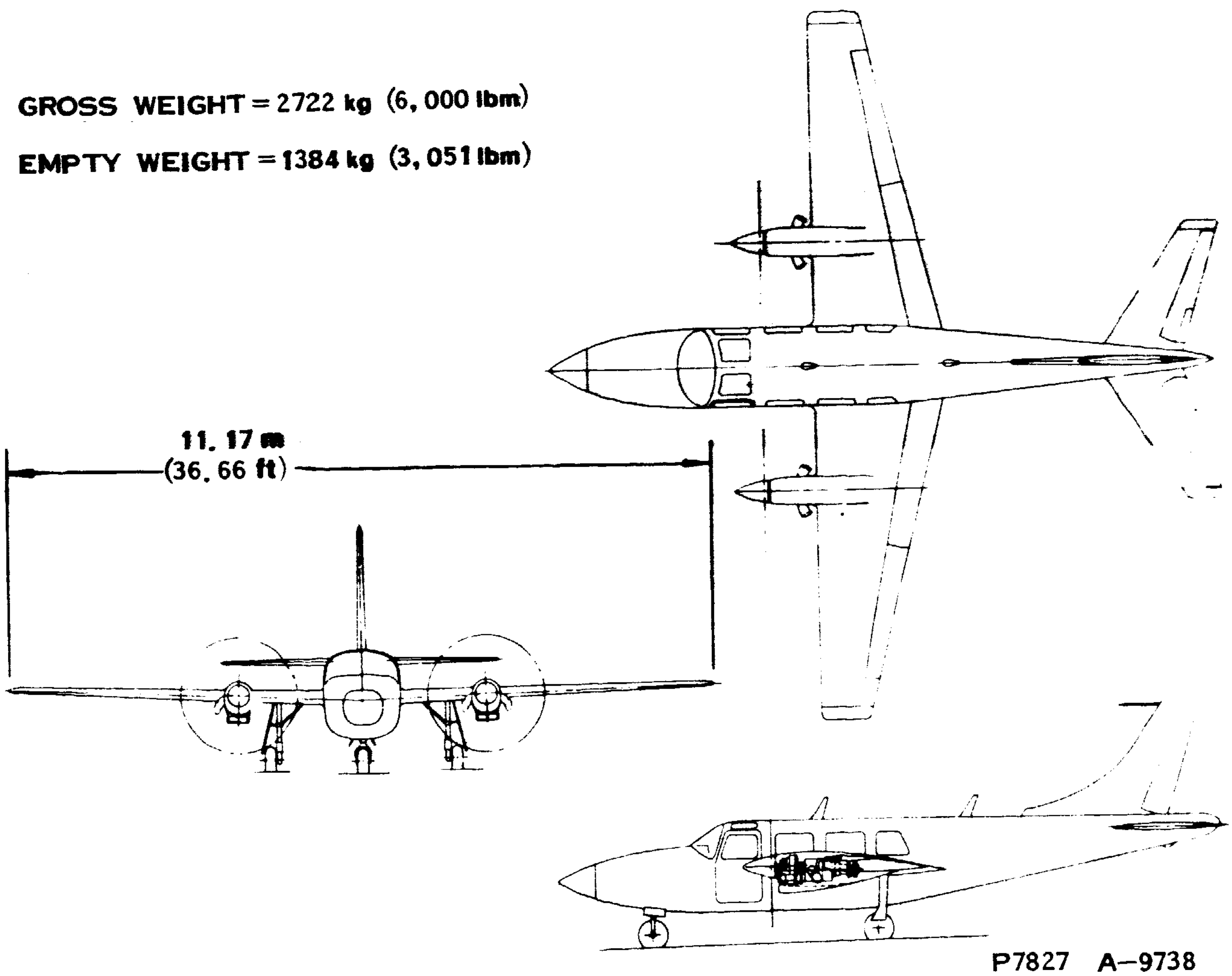

Figure 19. Turboprop Version of the Aerostar 601P

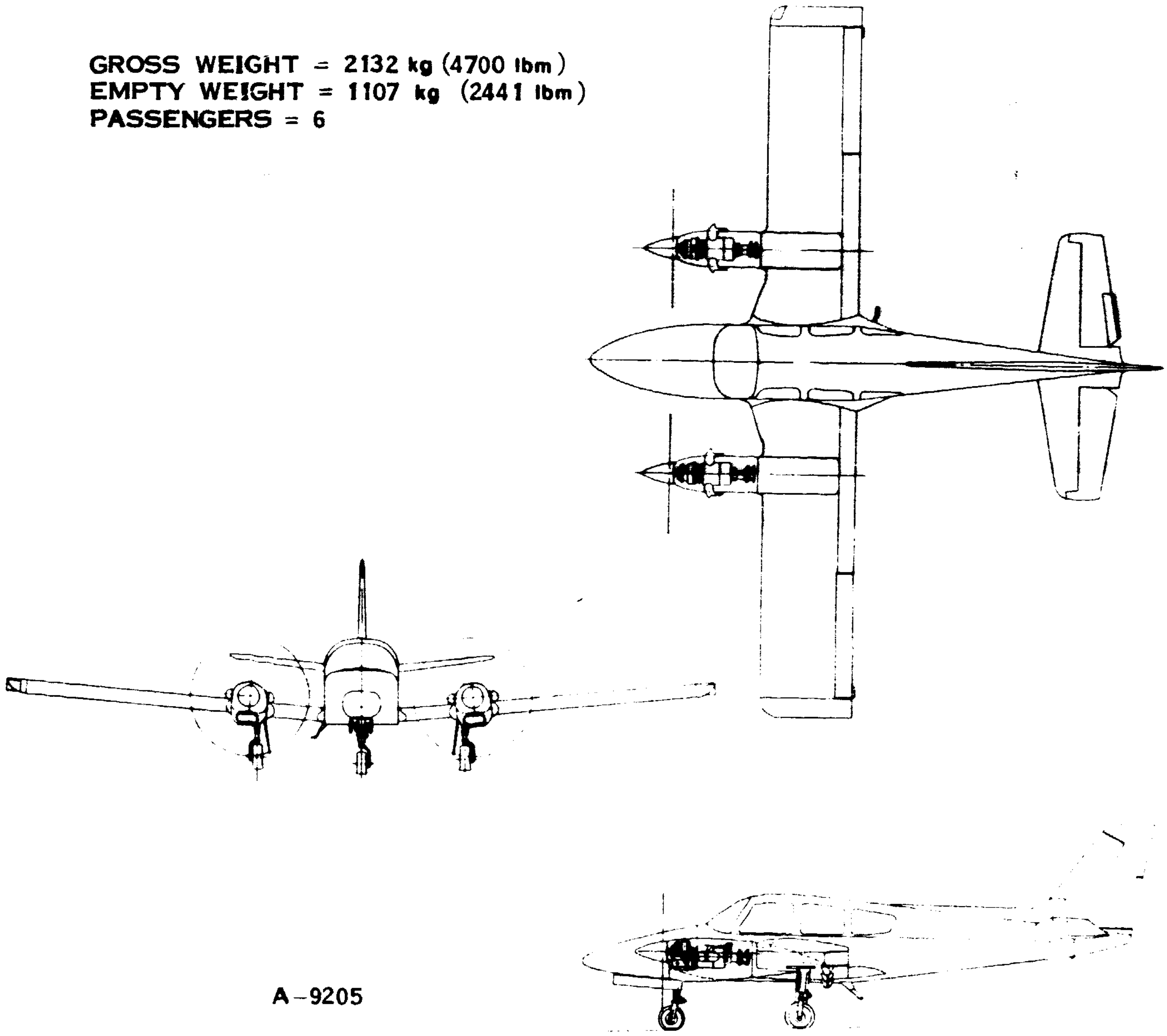

Figure 20. Turboprop Version of the Gulfstream American Cougar

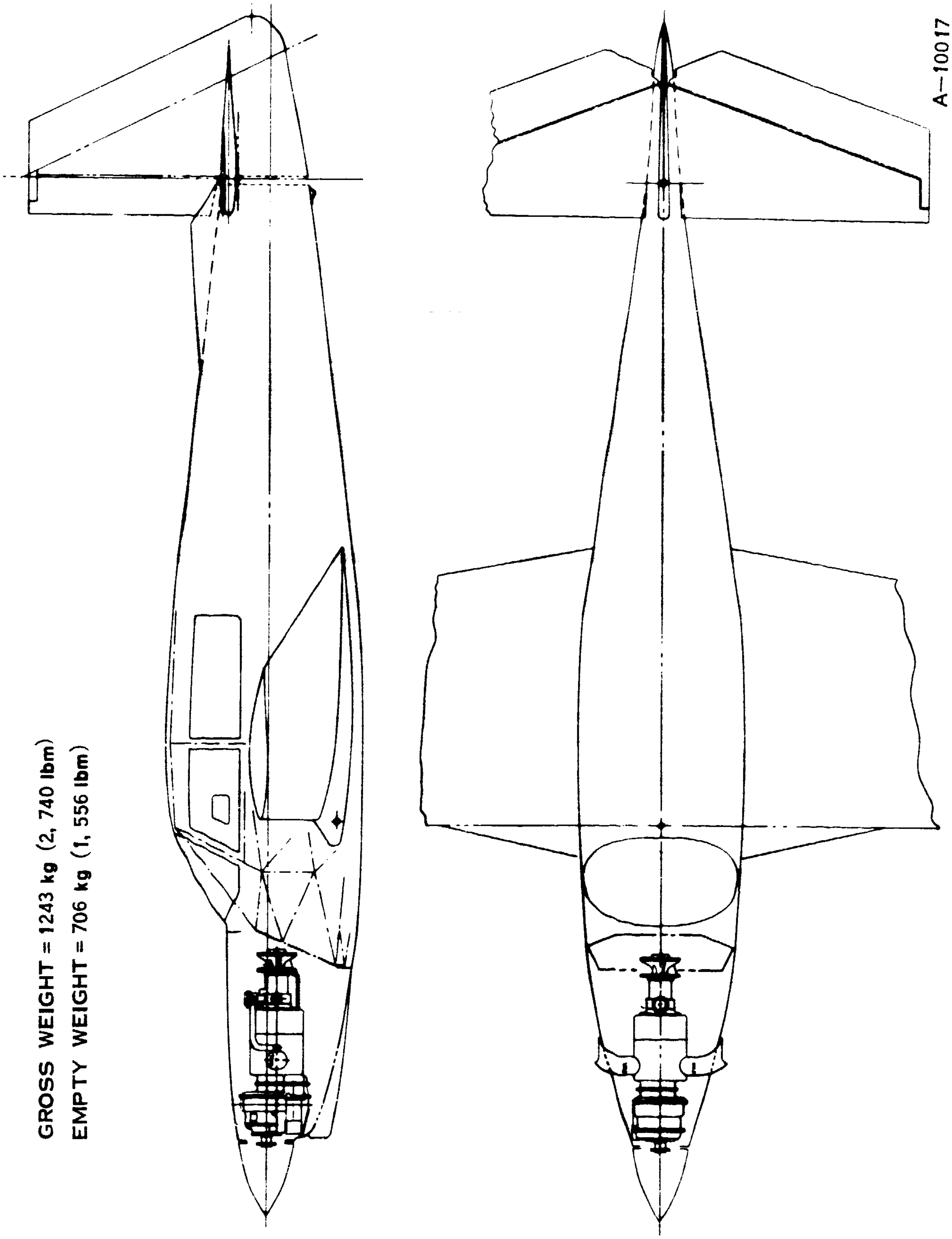

Figure 21. Mooney 201 Re-engined with P7757 Low Cost Turboprop

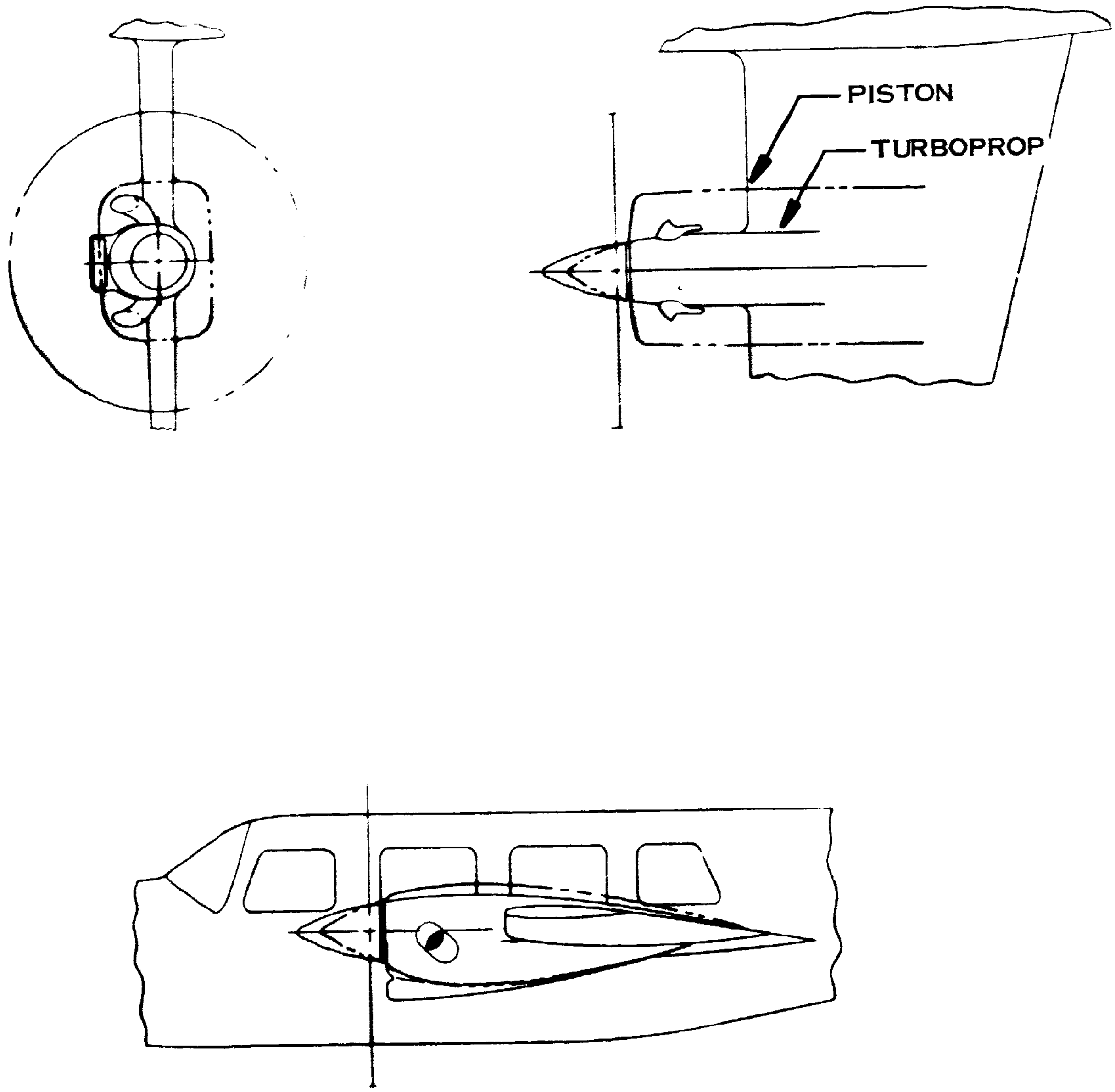

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Figure 22. Comparison of Aerostar Piston Engine Nacelle with Turboprop Engine Nacelle

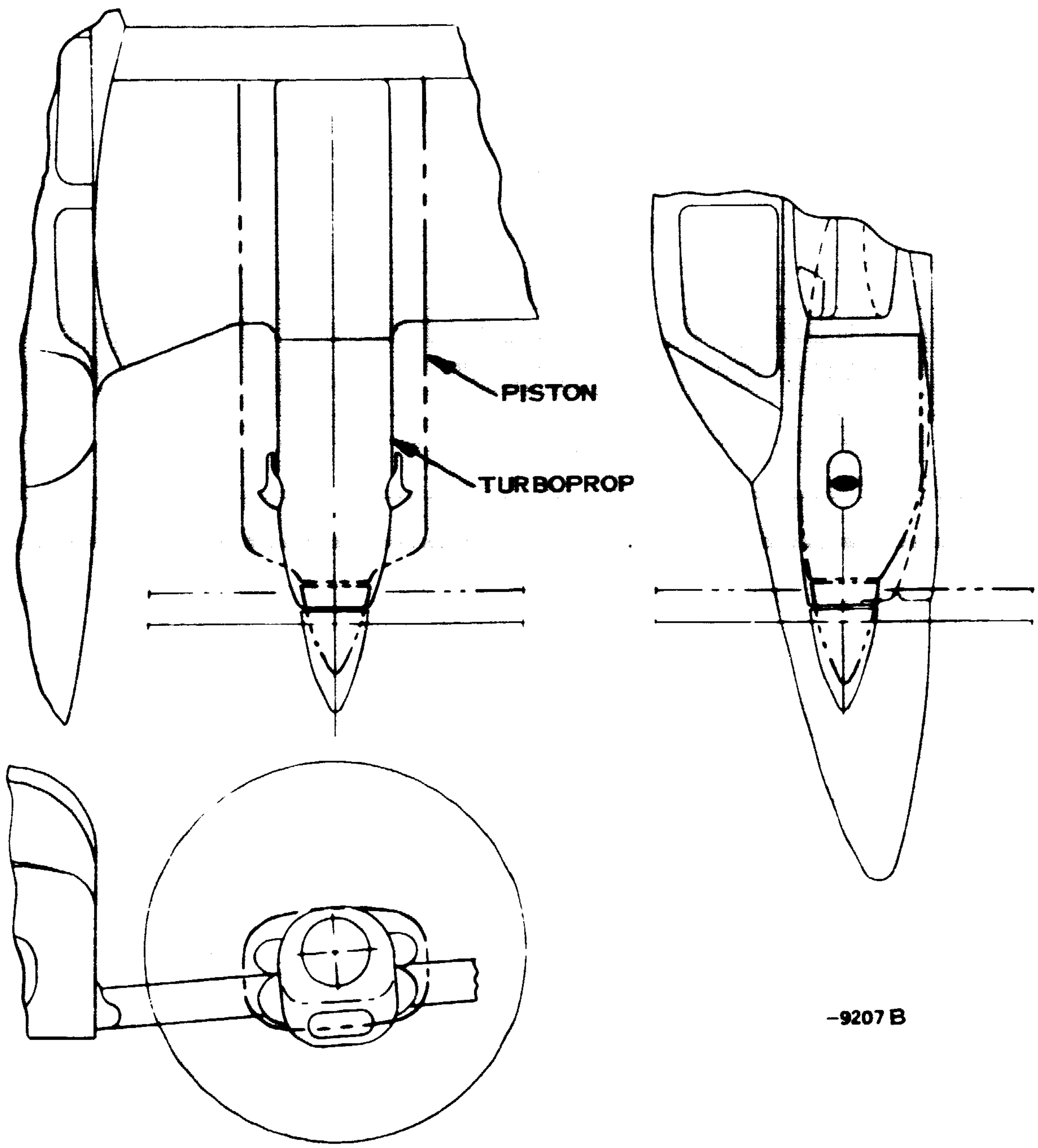


Figure 23. Comparison of Cougar Piston Engine Nacelle with Turboprop Engine Nacelle

TABLE XV. AEROSTAR 601P PERFORMANCE COMPARISON
(SI Units)

	POWERPLANT TYPE (SOURCE OF DATA)						
	TURBOPROP[1] (GASP)			PISTON (GASP)		PISTON (HANDBOOK)	
Persons on Board	6			6		6	
Gross Weight, kg	2722			2722		2722	
Pressurized, (ΔP), kPa	Yes, (51.7)			Yes, (29.3)		Yes, (29.3)	
Engine Rated kW, each	263			216		216	
Takeoff Distance (SL, Std Day, GW)							
Ground Run, m	309			396		395	
Over 15.2 m Obstacle, m	532			607		549	
Rate of Climb (SL, Std Day, GW), m/min	780			533		549	
Time to climb to 7620 m, min	15.4			21.8		21.0	
Maximum Cruise Speed, km/h	537			482		476	
Service Ceiling, m	10973			8534		8534	
Range (45 min Reserve)							
Altitude, m	4572	7620	10668	4572	7620	4572	7620
Range, km	2484	3471	4186	1020[2]	1120[2]	1109[2]	1217[2]
Speed, km/h	444	448	432	437	443	428	441
Max Fuel with 6 on Board[3], 1	931	931	931	450	443[4]	450	450
km/1	3.17	4.36	5.34	3.27	3.80	3.23	3.78
Seat-km/1	18.98	26.17	32.05	19.57	22.80	19.37	22.65
Landing Distance (SL, Std Day, GW)							
Over 15.2 m Obstacle, m	805			805		815	
Ground Roll, m	305[5]			304		302	

1 TIT for takeoff 55°K, for climb = 1228°K, and for cruise = 1200°K maximum. Fuel flow penalty for power extraction bleed assumed at 4.25%.

2 Reserve fuel calculated at 45 percent power (handbook) and cruise power (GASP).

3 Assumes 90.7 kg for each passenger and his baggage.

4 Empty weight varies according to cabin pressure differential required to limit cabin altitude to 2438 m. Fuel load is reduced in accordance with growth in empty weight.

5 Can be substantially shortened with reverse thrust.

TABLE XV. AEROSTAR 601P PERFORMANCE COMPARISON
(English)

	POWERPLANT TYPE (SOURCE OF DATA)						
	TURBOPROP[1] (GASP)			PISTON (GASP)		PISTON (HANDBOOK)	
Persons on Board	6			6		6	
Gross Weight, lbm	6,000			6,000		6,000	
Pressurized, (ΔP), psi	Yes, (7.5)			Yes, (4.25)		Yes, (4.25)	
Engine Rated hp, each	352			290		290	
Takeoff Distance (SL, Std Day, GW)							
Ground Run, ft	1,014			1,300		1,296	
Over 50 ft Obstacle, ft	1,746			1,992		1,800	
Rate of Climb (SL, Std Day, GW), ft/min	2,560			1,750		1,800	
Time to Climb to 25,000 ft, min	15.4			21.8		21.0	
Maximum Cruise Speed, knots	290			260		257	
Service Ceiling, ft	36,000			28,000		28,000	
Range (45 min reserve)							
Altitude, ft	15,000	25,000	35,000	15,000	25,000	15,000	25,000
Range, nm	1,341	1,874	2,260	551[2]	605[2]	599[2]	657[2]
Speed, knots	240	242	233	236	239	231	238
Max Fuel with 6 on Board[3], gal	246	246	246	119	117[4]	119	119
nm/gal	6.47	8.92	10.92	6.68	7.77	6.60	7.72
Seat-nm/gal	38.8	53.5	65.5	40.0	46.6	39.6	46.3
Landing Distance (SL, Std Day, GW)							
Over 50 ft Obstacle, ft	2,642			2,640		2,675	
Ground Roll, ft	1,000[5]			997		990	

1 TIT for takeoff = 1,800°F, for climb = 1,750°F, and for cruise = 1,700°F maximum. Fuel flow penalty for power extraction and bleed assumed at 4.25%.

2 Reserve fuel calculated at 45 percent power (handbook) and cruise power (GASP).

3 Assumes 200 lbm for each passenger and his baggage.

4 Empty weight varies according to cabin pressure differential required to limit cabin altitude to 8,000 ft. Fuel load is reduced in accordance with growth in empty weight.

5 Can be substantially shortened with reverse thrust.

TABLE XVI. AEROSTAR 601P WEIGHT BREAKDOWN COMPARISON (GASP DATA)

COMPONENT/GROUP	TURBOPROP		PISTON	
	kg	lbm	kg	lbm
Propulsion Group				
Primary Engines	161	354	504	1112
Primary Engine Installation	45	100	96	211
Fuel System	30	67	15	32
Propulsor Weight	82*	180*	86	190
Total Propulsion Group Weight	318	701	701	1545
Structures Group				
Wing	261	576	261	576
Horizontal Tail	33	72	32	71
Vertical Tail	17	37	16	36
Fuselage	239	528	228	502
Landing Gear	122	270	122	269
Primary Engine Section	52	114	127	280
Total Structures Group Weight	725	1598	786	1734
Flight Controls Group				
Cockpit Controls	10	23	10	23
Fixed Wing Controls	40	88	35	77
Total Controls Group Weight	50	111	45	100
Weight of Fixed Equipment	291	641	291	641
Weight Empty	1384	3051	1823	4020
Fixed Useful Load (Inc. Crew of 1)	125	275	125	275
Operating Weight Empty	1509	3326	1948	4295
Payload	454	1000	454	1000
Fuel	759	1674	320	705
Gross Weight	2722	6000	2722	6000

* 1988 Technology Propellers (composite blades) assumed.

TABLE XVII. AEROSTAR 601P DRAG COEFFICIENT BUILDUP COMPARISON
(GASP DATA)

COMPONENT	TURBOPROP C_{D_o}[1]	PISTON C_{D_o}[2]
Wing	0.00837	0.00795
Fuselage	0.00732	0.00702
Vertical Tail	0.00088	0.00083
Horizontal Tail	0.00230	0.00218
Engine Nacelles	0.00208	0.00294
Cooling Drag	0	0.00150
Total	0.02095	0.02242

Turboprop $C_D = 0.0209 + 0.0506\ C_L^2$

Piston $C_D = 0.0224 + 0.0510\ C_L^2$

Flight conditions for Reynolds number and skin friction calculation:

1 Turboprop - M = 0.400 at 10668 m (231 knots at 35,000 feet)

2 Piston - M = 0.300 at 4572 m (188 knots at 15,000 feet)

TABLE XVIII. GULFSTREAM AMERICAN COUGAR PERFORMANCE COMPARISON (SI Units)

	TURBOPROP[1]		PISTON
Passengers	6		4
Gross Weight - kg	2132		1724
Pressurized, (ΔP) - kPa	Yes (20.7)		No
Engine Rated kW, each	227		119
Takeoff Distance (SL, Std Day, GW)			
Ground Run - m	237		305
Over 15.2 m Obstacle - m	521		564
Flap Setting - rad	0.349		0.262
Rate of Climb (SL, Std Day, GW) - m/min	914		366
Time to Climb to 4572 m - min	6.2		30 (appx)
Maximum Cruise Speed - km/h	491		311
Service Ceiling - m	11582		5578
Range (45 min reserve)			
Altitude - m	4572	7620	2591
Range - km	1241	1791	859
Speed - km/h	326	380	296
Max. Fuel With Full Seats & Bags[2] - l	537.5	537.5	283.9
km/l	2.94	4.18	4.35
Seat-km/l	17.6	25.1	17.4
Landing Distance (SL, Std Day, GW)			Maximum Performance
Over 15.2 m Obstacle - m	427		405
Ground Roll - m	238[3]		216
Flap Setting - rad	0.698		0.419

1 TIT for takeoff and climb = 1200°K. Maximum Cruise TIT = 1144°K. Fuel flow penalty for power extraction and bleed assumed at 4.25%.

2 Assumes 90.7 kg for each passenger and his baggage.

3 Can be substantially shortened with reverse thrust.

TABLE XVIII. GULFSTREAM AMERICAN COUGAR PERFORMANCE COMPARISON (English)

	TURBOPROP[1]		PISTON
Passengers	6		4
Gross Weight - lbm	4,700		3,800
Pressurized, (ΔP) - psi	Yes, (3)		No
Engine Rated hp, each	305		160
Takeoff Distance (SL, Std Day, GW)			
Ground Run - ft	**779**		**1,000**
Over 50 ft Obstacle - ft	**1,710**		**1,850**
Flap Setting - deg	**20**		**15**
Rate of Climb (SL, Std Day, GW) - ft/min	**3,000**		**1,200**
Time to Climb to 15,000 ft - min	**6.2**		**30 (appx)**
Maximum Cruise Speed - knots	**265**		**168**
Service Ceiling - ft	**38,000**		**18,300**
Range (45 min reserve)			
Altitude - ft	15,000	25,000	8,500
Range - nm	670	967	464
Speed - knots	176	205	160
Max. Fuel With Full Seats & Bags[2] - gal	142	142	75
nm/gal	6.00	8.55	8.89
Seat-nm/gal	36.0	51.3	35.6
Landing Distance (SL, Std Day, GW)			Maximum Performance
Over 50 ft Obstacle - ft	1,402		1,330
Ground Roll - ft	781[3]		710
Flap Setting - deg	40		24

1 TIT for takeoff and climb = 1700°F. Maximum Cruise TIT = 1600°F. Fuel flow penalty for power extraction and bleed assumed at 4.25%.

2 Assumes 200 lbm for each passenger and his baggage.

3 Can be substantially shortened with reverse thrust.

TABLE XIX. MOONEY 201 PERFORMANCE COMPARISON
(SI Units)

	POWERPLANT TYPE AND (SOURCE OF DATA)				
	TURBOPROP[1] (GASP)		PISTON (GASP)	PISTON (HANDBOOK)	
Passengers	4		4	4	
Gross Weight - kg	1243		1243	1243	
Pressurized, (ΔP) - kPa	Yes (51.7)		No	No	
Engine Rated kW	227		149	149	
Takeoff Distance (SL, Std Day, GW)				Short	Normal
Ground Run - m	172		285	271	284
Over 15.2 m Obstacle - m	404		503	463	540
Rate of Climb (SL, Std Day, GW) - m/min	745		311	312	
Time to Climb to 4572 m - min	7.6		26	25	
Maximum Speed - km/h	450		324	324	
Service Ceiling - m	12192		5700	5700	
Range (45 Min Reserve)					
Altitude - m	7620	10668	2438	2438	
Range - km	1067	1345	970	995	
Speed - km/h	328	361	300	300	
Max Fuel with 4 Pssgrs[2] - l	196.8	196.8	170.3	170.3	
km/l	7.80	10.02	7.47	7.72	
Seat-km/l	31.2	40.1	29.9	30.9	
Landing Distance (SL, Std Day, GW)				Maximum Performance	
Over 15.2 m Obstacle - m	489		488	491	
Ground Roll - m	238[3]		238	235	

1 TIT for takeoff and climb = 1200°K. Maximum cruise TIT = 1200°K. Fuel flow penalty for power extraction and bleed assumed at 4.25%.
2 Assumes 90.7 kg for each passenger and his baggage.
3 Can be substantially shortened with reverse thrust.

TABLE XIX. MOONEY 201 PERFORMANCE COMPARISON (English)

	POWERPLANT TYPE AND (SOURCE OF DATA)				
	TURBOPROP[1] (GASP)		PISTON (GASP)	PISTON (HANDBOOK)	
Passengers	4		4	4	
Gross Weight - lbm	2,740		2,740	2,740	
Pressurized, (ΔP)-psi	Yes (7.5)		No	No	
Engine Rated hp	305		200	200	
Takeoff Distance (SL, Std Day, GW)				Short	Normal
Ground Run - ft	564		934	890	931
Over 50 ft Obstacle - ft	1,325		1,649	1,518	1,771
Rate of Climb (SL, Std Day, GW) - ft/min	2,445		1,020	1,023	
Time to Climb to 15,000 ft - min	7.6		26	25	
Maximum Speed - knots	243		175	175	
Service Ceiling - ft	40,000		18,700	18,700	
Range (45 Min Reserve)					
Altitude - ft	25,000	35,000	8,000	8,000	
Range - nm	576	726	524	537	
Speed - knots	177	195	162	162	
Max Fuel with 4 Pssgrs[2] - gal	52	52	45	45	
nm/gal	15.95	20.49	15.27	15.78	
Seat-nm/gal	63.8	82.0	61.1	63.1	
Landing Distance (SL, Std Day, GW)				Maximum Performance	
Over 50 ft Obstacle - ft	1,603		1,602	1,610	
Ground Roll - ft	780[3]		780	770	

1 TIT for takeoff and climb = 1700°F. Maximum cruise TIT = 1700°F. Fuel flow penalty for power extraction and bleed assumed at 4.25%.
2 Assumes 200 lb for each passenger and his baggage.
3 Can be substantially shortened with reverse thrust.

TABLE XX. MOONEY 201 WEIGHT BREAKDOWN COMPARISON (GASP DATA)

COMPONENT/GROUP	TURBOPROP		PISTON	
	kg	lbm	kg	lbm
Propulsion Group				
Primary Engine	80	177	179	394
Primary Engine Installation	23	50	24	53
Fuel System	19	42	16	35
Propulsor Weight	40	88	29	64
Total Propulsion Group Weight	162	357	248	547
Structures Group				
Wing	132	290	132	290
Horizontal Tail	26	57	24	54
Vertical Tail	12	27	12	26
Fuselage	194	427	149	328
Landing Gear	47	103	47	103
Total Structures Group Weight	410	904	364	802
Flight Controls Group				
Cockpit Controls	9	20	9	20
Fixed Wing Controls	15	34	14	30
Total Controls Group Weight	25	55	23	50
Weight of Fixed Equipment	109	240	109	240
Weight Empty	706	1556	743	1638
Fixed Useful Load (Inc. Crew of 1)	104	230	104	230
Operating Weight Empty	810	1786	847	1868
Payload	272	600	272	600
Fuel	161	354	123	272
Gross Weight	1243	2740	1243	2740

TABLE XXI. MOONEY 201 DRAG COEFFICIENT BUILDUP COMPARISON (GASP DATA)

COMPONENT	TURBOPROP C_{D_o} [1]	PISTON C_{D_o} [2]
Wing	0.00870	0.00835
Fuselage	0.00580	0.00546
Vertical Tail	0.00069	0.00067
Horizontal Tail	0.00184	0.00176
Cooling Drag	0	0.00130
Total	0.01703	0.01753

Turboprop $C_D = 0.0170 + 0.0514\ C_L^2$

Piston $C_D = 0.0175 + 0.0515\ C_L^2$

Flight conditions for Reynolds number and skin friction calculations:

1 **Turboprop** - M = 0.32 at 7620 m (193 knots at 25,000 feet)

2 Piston - M = 0.249 at 2438 m (160 knots at 8000 feet)

The rate of climb of the retrofitted Mooney has been more than doubled as has the altitude capability (Table XIX). A modest range improvement is also shown which would have been better had the cabin design ΔP for pressurization been lower and the corresponding fuselage weight increase less (Table XX). The turboprop Model 201 has sufficient excess power to permit an increase in the certificated gross weight and an increase in allowable fuel load. This action could lead to a substantial increase in range capability.

These airplane trade studies have demonstrated that the turboprop can provide benefits to general aviation through enhanced airplane performance. The general aviation pilot must be willing to operate his airplane at altitudes above 4572 m (15,000 ft) to maximize the gains, however, and this requires that most operations be by instrument-rated pilots under controlled flight conditions. By 1988 the percentage of controlled flight operations is expected to be substantially higher than today, and the instrument-rated pilot population is expected to grow from today's 222,000 to about 380,000. Thus there should be little shyness among the pilots of that era about high-altitude operations. The conceptual engine can therefore be considered able to surmount the fuel efficiency impediment that has constrained small turbine engine sales (ref 11), at least for business-use airplane applications.* It must also be able to pass through the first cost and LCC barriers. The feasibility of this is discussed in the LCC subsection.

TURBOFAN

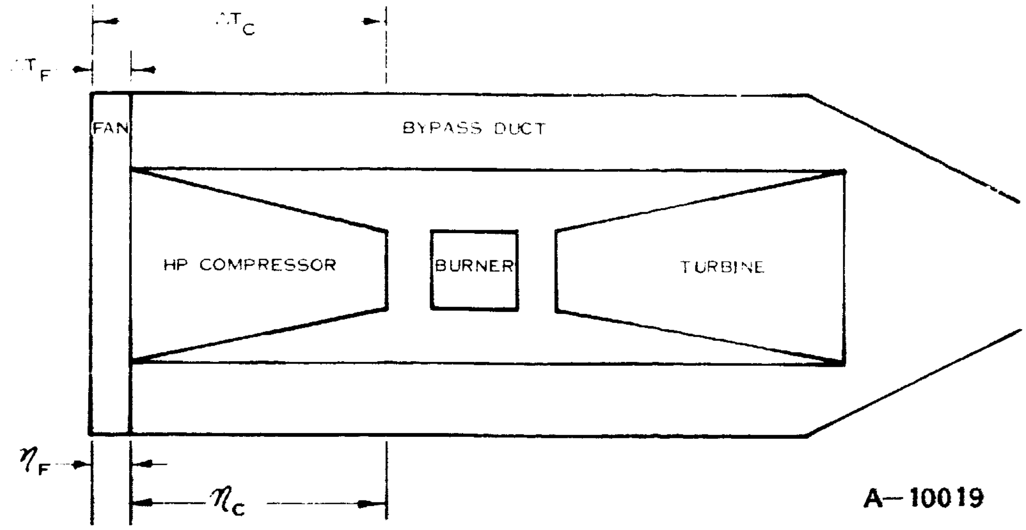
Parametric Study

Parametric performance data were generated to facilitate T/F performance optimization studies. Data plots were used to show the relationship between TSFC and specific thrust for several compressor temperature rise values between 167°K and 444°K (300°F and 800°F) and several bypass ratios. The ΔT of compression was selected to be a variable rather than the conventional compressor pressure ratio, because this form of presentation is believed more representative of actual operational modes of turbine engines. Also, a better understanding is gained of how specific compressors will operate at varying inlet temperatures. Figure 24 is a schematic of the parametric study T/F engine and includes a list of study assumptions, variable values, and nomenclature. Samples of the type of parametric curves generated are shown in Figures 25 and 26.

Turbofan Design Characteristics Selection

The selection of a design concept for a turbofan is as complex a process as the previously discussed turboprop design selection procedure. First, the maximum takeoff and cruise turbine temperatures are selected. The maximum takeoff turbine temperature and the maximum cruise temperature chosen here were based on the design philosophy that the achievement of very long life hot section rotors as manufactured by low cost fabrication techniques will require compromise in the design

*The piston engine is probably superior for instructional, recreational, and most proficiency flying since these are usually done at low altitude and involve frequent changes in altitude and direction of flight. Such changes are not desirable in enroute airspace at altitudes above 3048 m (10,000 ft) where the 463 km/hr (250 knot) speed limit is not in effect. Instructional flying alone accounts for about 25 percent of all general aviation flight hours (ref 12).



A—10019

ENGINE ASSUMPTIONS

1) **Fuel heating value = 42800 kJ/kg** (18400 Btu/lb)

2) **Bypass duct pressure loss = 3.5 percent**

3) **Burner pressure loss =** 4.0 **percent**

4) **Burner efficiency = 99.5 percent**

5) **Thrust coefficient =** 0.985

6) **HP and LP turbine efficiencies =** 0.86

PARAMETRIC STUDY ASSUMPTIONS

1) **No power extraction or bleed**

2) **Ram recovery = 1.0**

3) **Bypass ratio (BPR) variable between 1 and 7**

4) ΔT compression (ΔTc) variable between 167°K (300°F) and 444°K (800°F).

5) Overall compression pressure ratio (P_r) defined by ΔTc and various compressor inputs

6) Fan temperature rise (ΔT_f) = 33°K (60°F), 44°K (80°F), and 56°K (100°F).

7) Turbine inlet temperature (TIT) = 1200°K (1700°F), 1311°K (1900°F) and 1422°K (2100°F).

8) At ΔT_f = 44°K (80°F); fan, HP compressor and turbine efficiencies (η_F, η_C, η_T) were varied to determine influence coefficients

9) SLS and Alt cruise at 0.6 Mach and 9144m (30,000 ft) were considered.

Figure 24. Schematic of the Parametric Study Turbofan Engine

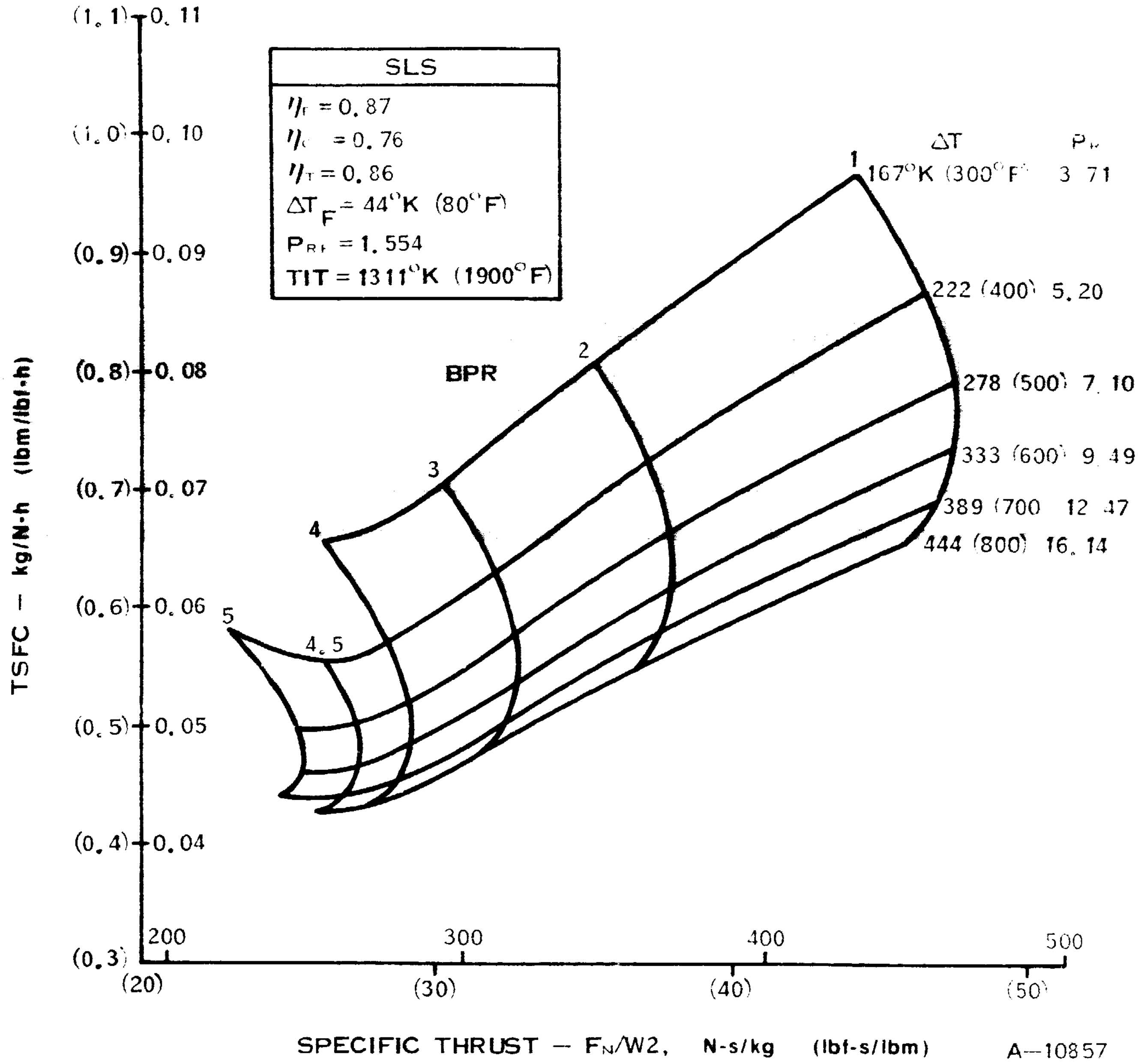


Figure 25. Turbofan Parametric Study Curves - SL/STD Day, $\eta_c = 0.76$, $\eta_T = 0.86$

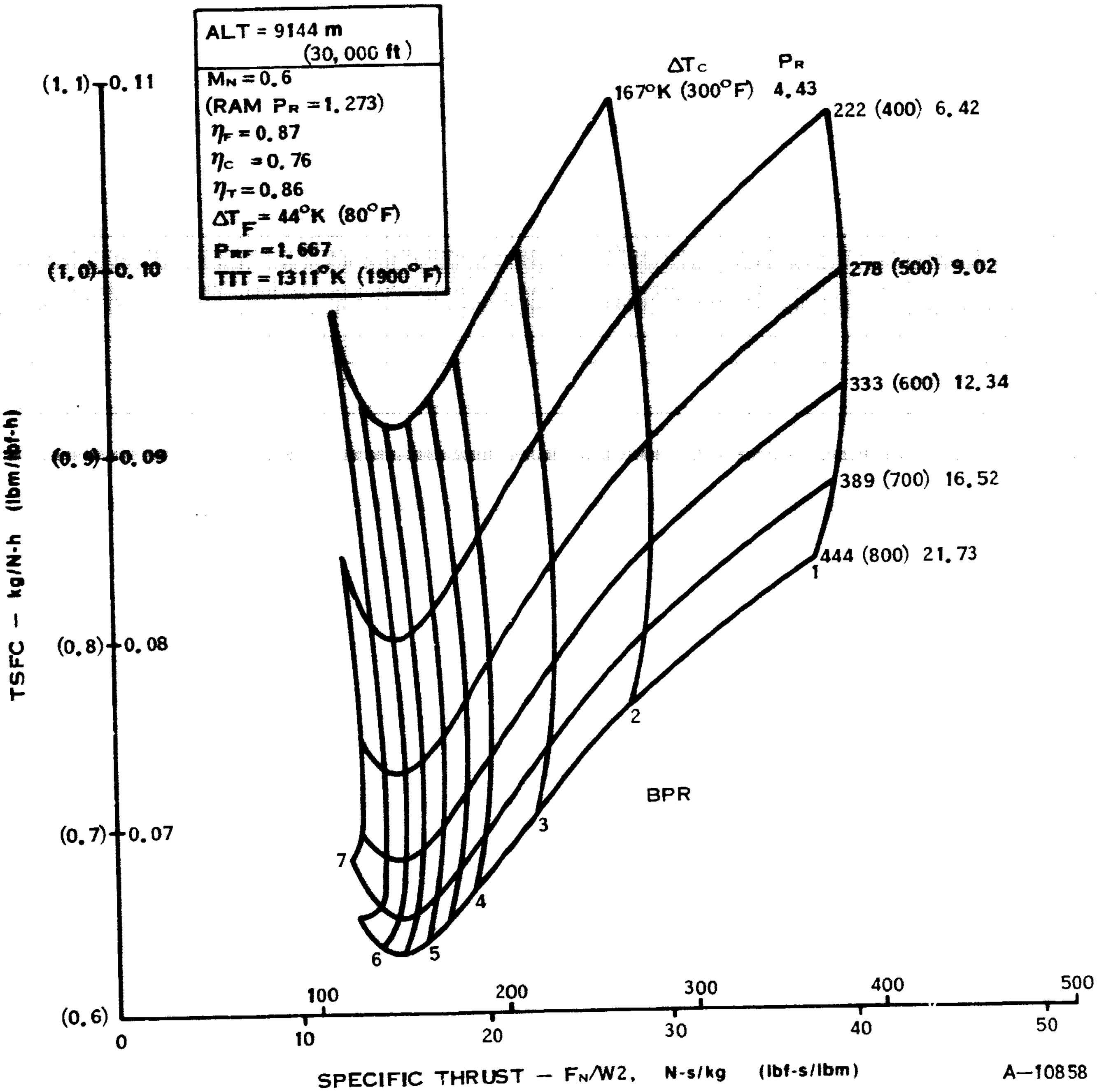


Figure 26. Turbofan Parametric Study Curves - 9144 m (30,000 ft)/Mach 0.6 $\eta_c = 0.76$, $\eta_T = 0.86$

stress levels of the materials used. Figure 27 illustrates existing and expected strength versus temperature characteristics of candidate turbine materials for the 1985/1990 timeframe. Conventional high speed spool turbine design generally puts blade stress in the 207 to 241 MPa (30,000 to 35,000 psi) region with blade temperature approximately 111°K (200°F) below gas temperature. Once a determination is made of the maximum turbine entry temperature, the selection of design compressor temperature rise and bypass ratio is considerably simplified. As an example, inspection of Figure 26, which is based on a 44°K (80°F) ΔT fan design at 9144 m (30,000 ft) and 0.6 Mach number shows that a bypass ratio of 4.5 to 5 with a pressure ratio of 20 approaches the optimum for a 1311°K (1900°F) TIT.

Presently used materials are exemplified by IN-100 or MAR-M 246. Very long TBOs (3000 to 6000 hr) can be attained by using these materials when gas temperatures are held to the 1255°K (1800°F) range. The low speed, low stress design (approximately one-half the blade stress of conventional designs) will permit higher temperatures, longer TBOs, or less stringent manufacturing techniques. Figure 27 shows several advanced materials which are of interest for improved versions of a basic turbine engine design. The materials are MA 6000E, DS EUTECTIC, and RSR. If characterization of MA 6000E proves to be as advantageous as it looks now, it will be of great interest for the low stress concept because it can operate at stress levels compatible with 1478°K (2200°F) temperatures with good life expectancy.

The advantages of cooling a small blade turbine were judged to be more than offset by cooling losses and blade shape compromises unless gas temperatures can be raised above 1478°K (2200°F). This would push optimum pressure ratio and bypass ratio higher to maintain the same specific fuel consumption. The result would be an increase in the cost of manufacture of both the hot end and the cold end of the engine and an increase in development cost and risk. For this reason it was judged more cost effective to utilize the low speed, low stress concept to produce low cost turbofan engines. These engines could operate at moderate turbine temperatures and have a potential for growth as advanced materials became real commercial engineering entities.

A turbine entry temperature of 1311°K (1900°F) would indicate that an optimum bypass ratio would be in the 4.5:1 to 5.5:1 range and require overall compression temperature rise values of 389°K to 444°K (700°F to 800°F). The 44°K (80°F) temperature rise fan upon which Figure 26 is based was judged to have the highest practical pressure rise for a single stage that would have good part speed performance and stability when designed with a low hub/tip ratio. The low hub/tip ratio is desirable to permit a high low-pressure-spool speed and thereby minimize intermediate compressor design and fabrication problems and reduce the required number of low pressure turbine stages. A further constraint on the temperature rise achievable in the fan arises from the desire for a low tip speed to minimize noise. This, of course, influences permissible rotational speed.

Parametric data was prepared for fans of other temperature rise capabilities and for engines having various component performance levels. Three basic turbofan design concepts, in addition to an evaluation of a "common core concept," were explored during the cost/performance trades. These included a geared fan F107-derivative engine, a tandem spool design, and a concentric-shaft, two-spool T/F.

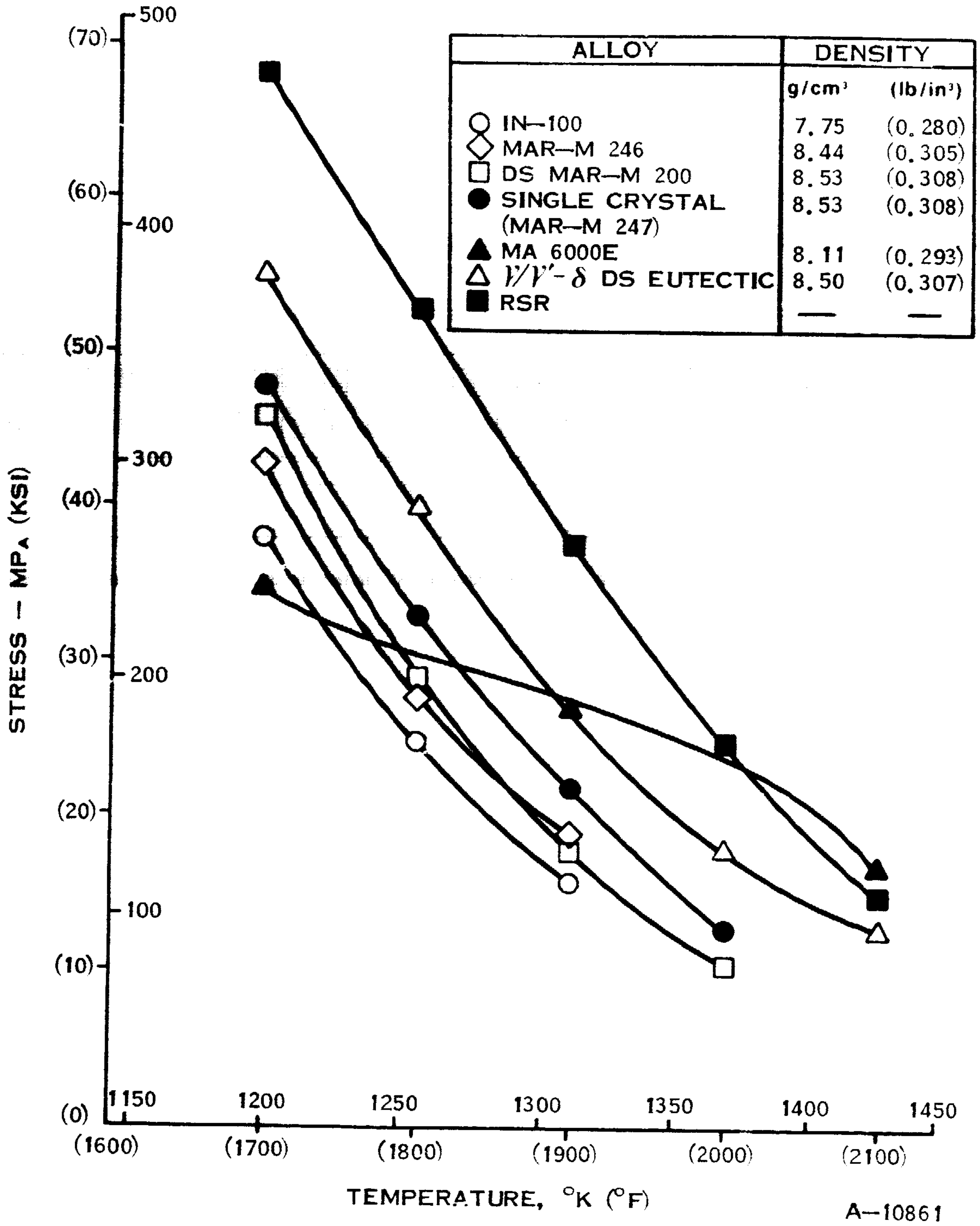


Figure 27. Nickel Base Blade Alloys - 100-Hour Rupture Strength

Geared Fan F107 Derivative

A sophisticated design based on the WR19 series of fan jet engines, of which the F107-WR-100 and F107-WR-400 for the ALCM and Tomahawk cruise missiles are the most notable versions, was evaluated. This design was characterized by a gear-driven fan stage and a four-stage intermediate pressure compressor with a three-stage low speed turbine in place of the present two-stage LP turbine. Figure 28 shows the external configuration of one version of this engine.

Tandem Spool T/F

In an effort to exploit core commonality and WRC low cost construction techniques, an unconventional turbofan design was generated. The concept was referred to as a "tandem spool fan" because the high pressure spool and the low pressure spool are located on completely independent shafts displaced axially. All HP spool accessories are located in the engine tailcone. A very low speed, two-stage fan of relatively high hub/tip ratio was chosen because it extended the low speed, low stress design philosophy to the practical limit.

The engine cycle was optimized through selection of the number of stages of IP compression. The general arrangement of components is shown in Figure 29. The performance level was found to be approximately 7 percent below that of the geared fan design, primarily because of additional duct losses resulting from the complicated flow passages and cross overs necessary to make the independent axial spools work.

Concentric-Shaft, Two-Spool T/F

The third design approach involved a more conventional, two-spool T/F constrained in configuration to enable use of the low cost, low stress design philosophy of the turboprop engine. A fan pressure ratio of 1.4 was selected for compatibility with the desired airplane performance, and the number of IPC stages was traded against design complexity and performance as shown in Figure 30. In this analysis the aerodynamics of the turboshaft core was held constant and changes to the cycle were achieved by varing only the low speed spool components.

Because manufacturing cost is insensitive to the number of stages when using the low cost design concept, decisions as to optimum stage numbers must be based on other considerations involving dynamics, aerodynamic stability, and bearing suspension complexity. The design point chosen was at a bypass ratio of 5.2:1 and a maximum cruise turbine temperature of 1283°K (1850°F). The logic behind the chosen design TIT is the expectation that 1283°K (1850°F) turbine temperatures can be tolerated in uncooled low cost/low stress components in the 1988 timeframe. Stress levels approximately one half that of conventional design practice will ensure a very long life. As material temperature tolerance and cooling technology advance, increases in turbine temperature and engine performance can be anticipated while maintaining the low life cycle cost environment generated by the original long life components. Required adjustment in cycle pressure ratio for the improved engines would be accommodated by improved compressor efficiencies and increases in work level of the compressor components.

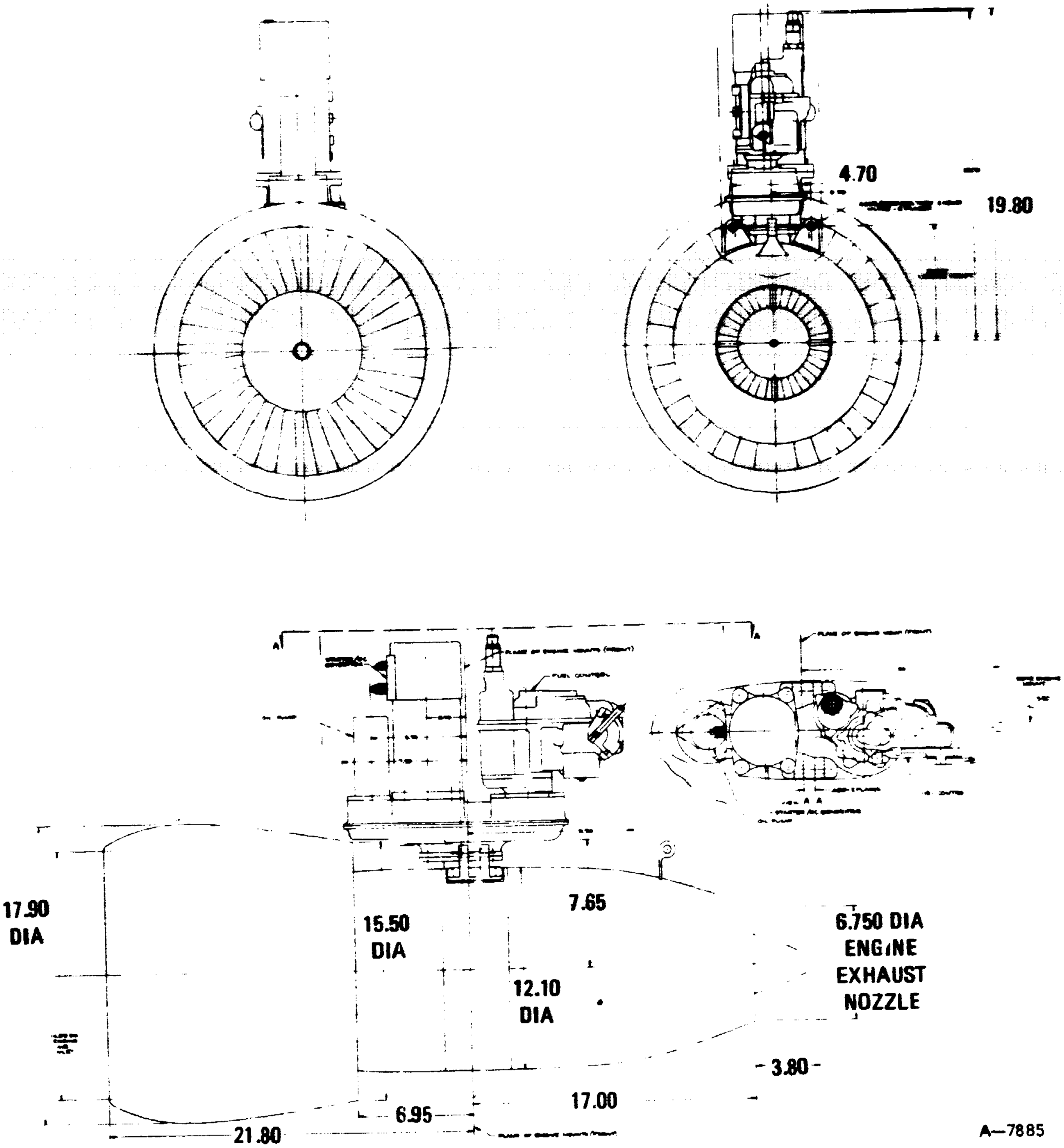


Figure 28. Geared Fan - 1000 Pound Thrust Class F107 Derivative Turbofan

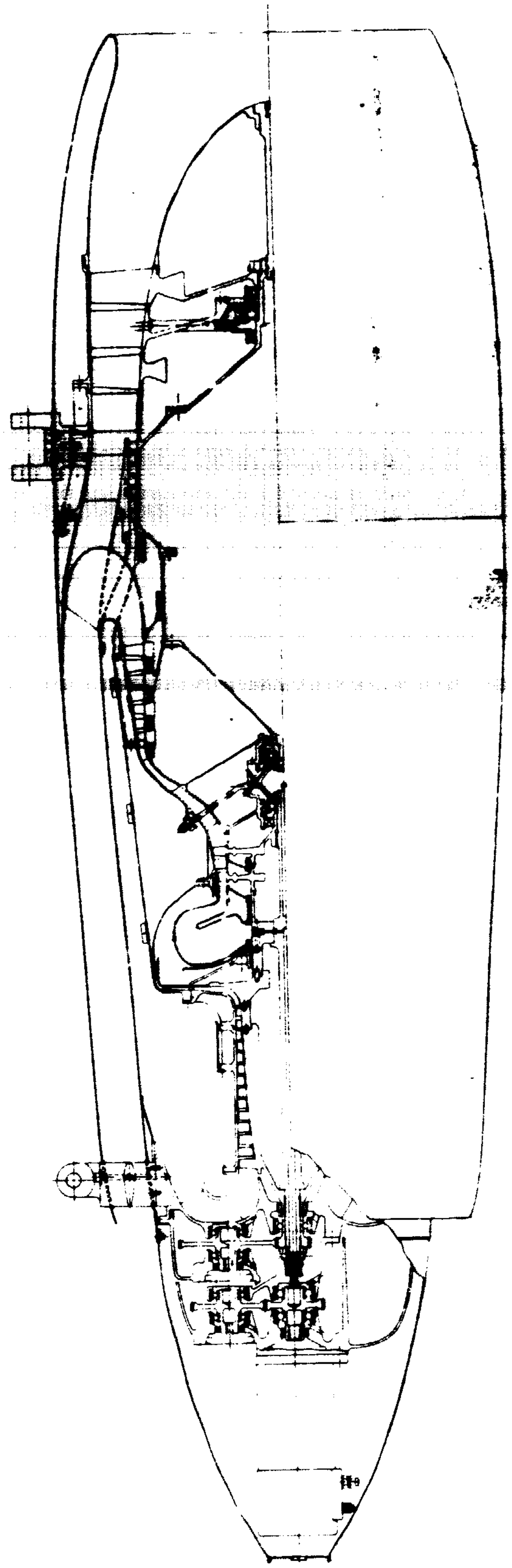


Figure 29. Cutaway of Tandem Spool Turbofan (P7806)

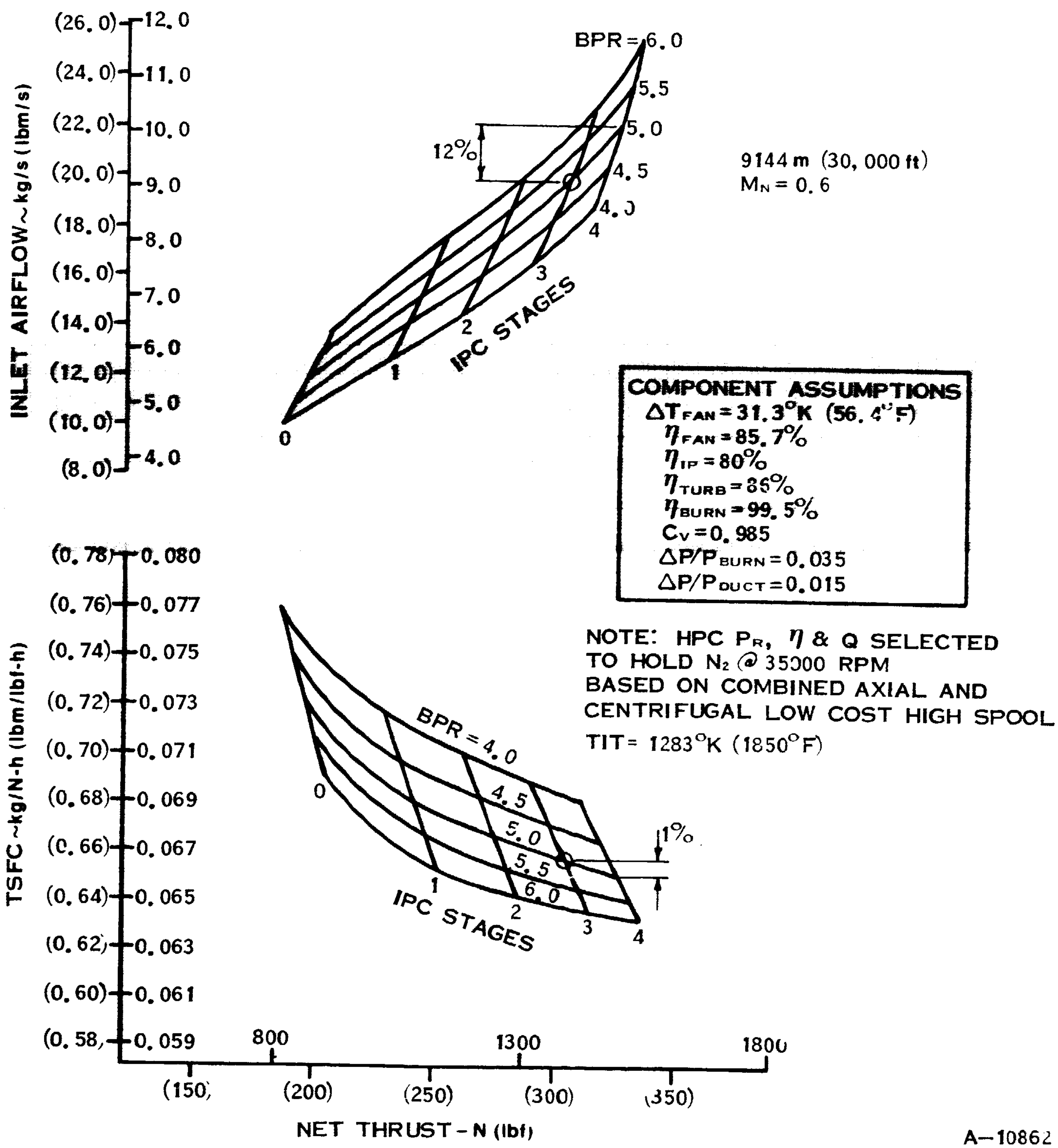


Figure 30. Low Cost Conventional Turbofan Design Concept Optimization Study - 9144 m (30,000 ft)/Mach 0.6

Preferred Concept

Analysis of the three design concepts showed that the performance and weight of the geared fan design and the low cost concentric-shaft conventional spool design were comparable. The cost of the geared fan design was more than twice that of the low cost conventional spool design, however. The performance of the tandem spool design was 7 percent below that of the low cost conventional spool engine, its weight was 60 percent greater, and the cost was 7 percent higher. On the basis of this comparison, the decision was made to narrow the study to the low cost conventional spool design. The final version of this preferred design, termed the P7808 turbofan, is shown in Figure 39.

Turbofan P7808

The P7808 turbofan is configured to use the T/P power section as a gas generator with a conventional, concentric, low speed-spool shaft system. As sized, the T/P core is appropriate for an efficient T/F engine in the 4448-N-thrust (1000-lb-thrust) class. The core is comprised of a six-stage axial compressor followed by a centrifugal compressor, annular combustor, and two-stage turbine. The low-pressure (LP) shaft system includes a fan that produces a pressure ratio to 1.4 followed by a three-stage, intermediate-pressure (IP) compressor and a four-stage, low-speed turbine. The three-stage IP compressor and four-stage LP turbine were selected through a trade study involving shaft dynamics and data as shown in Figure 30.

Table XXII is a component performance summary for a nominally-rated P7808 engine at the SL/static condition and the Mach 0.6 cruise condition at 9144 m (30,000 ft). Note the excellent cruise SFC for this under-4448 N (under-1000 lb) thrust engine. Figures 31 and 32 show the net thrust, Mach number and SFC relationship for SL, standard day, and 9144 m (30,000 ft) flight conditions. Figure 33 illustrates the clean lines of the engine's external surface resulting from internally-mounted accessories and plumbing. This arrangement obviates the need for, and saves the weight of, a separate engine nacelle.

Airplane Studies

To aid in the evaluation and selection of the most suitable T/F engine of the three that were considered (tandem spool, geared fan, and two spool), airplane performance analyses were made using each candidate. The analyses involved a basic six-place twin T/F airplane weighing 2722 kg (6,000 lbm) as defined by the market study. Limited work was also done with an eight-place version of the same airplane. Because the baseline airplane had aft pod-mounted engines, weight and balance computations were made to ensure engine compatibility. One engine, the tandem-spool configuration, was judged too heavy and a liability from the weight/balance/stability standpoint for the type of airplane design being considered. This finding and engine cost considerations led to the elimination of the tandem-spool candidate. The high cost of the geared fan candidate led to its elimination.

Figure 34 illustrates the baseline airplane with the two-spool P7808 engine installed. The GASP-derived performance of this airplane/engine combination is shown in Table XXIII. For comparitive purposes, the performance of T/P and piston versions of the Aerostar 601P are also shown in this table. Note with respect to fuel efficiency, that the numbers favor the T/P Aerostar. Note also that the turbofan-powered airplane compares very favorably with the piston-powered Aerostar 601P. Its range is much greater with the same payload because the lighter-weight turbofan engines permit more than twice as much fuel to be carried, (Table XXIV).

TABLE XXII. TURBOFAN ENGINE F7808 COMPONENT PERFORMANCE SUMMARY (Sheet 1 of 2) (SI Units)

	Takeoff	Cruise
Alt. - m	0	9144
M_N	0	0.6
Ta - °K	288.2	228.7
Pa - kPa	101.325	30.089
Rating		
Fn - N	4346	1112
SFC - kg/N-h	0.040	0.069
TIT - °K	1333	1244
BPR	5.32	5.22
Win - kg/s	18.1	8.92
N_1 - rpm	11660	11870
N_2 - rpm	35000	34320
P_r Compressor	15.52	19.82
Compressor Performance		
Fan:		
Q_{in} - (kg/s) $\sqrt{°K}$/kPa	3.025	3.640
P_r	1.336	1.407
η	0.863	0.862
ΔT - °K	28.9	29.3
IPC:		
Q_{in} - (kg/s) $\sqrt{°K}$/kPa	0.376	0.440
P_r	1.858	2.069
η	0.791	0.797
ΔT - °K	77.3	79.5
HPC:		
Q_{in} - (kg/s) $\sqrt{°K}$/kPa	0.226	0.241
P_r	6.251	6.806
η	0.744	0.749
ΔT - °K	348	333
Burner Performance		
Q_{in} - (kg/s) $\sqrt{°K}$/kPa	0.050	0.049
P_r	0.965	0.965
η @ 42800 kJ/kg	0.995	0.995
Fuel/Air	0.0971	

TABLE XXII. TURBOFAN ENGINE P7808 COMPONENT PERFORMANCE SUMMARY (Sheet 2 of 2)
(SI Units)

Turbine Performance		
HP Turbine:		
Q_{in} - (kg/s) $\sqrt{^{\circ}K}$/kPa	0.070	0.070
P_r	3.496	3.596
η	0.86	0.86
LP Turbine:		
Q_{in} - (kg/s) $\sqrt{^{\circ}K}$/kPa	0.216	0.221
P_r	3.161	3.573
η	0.86	0.86
$(\Delta P/P)_{BPD}$	0.011	0.015
%(WL/Wcore)	1.0	1.0
CF-Primary	0.982	0.990
CF-Secondary	0.980	0.989

TABLE XXII. TURBOFAN ENGINE P7808 COMPONENT PERFORMANCE SUMMARY (Sheet 1 of 2) (English)

	Takeoff	Cruise
Alt. - ft	0	30,000
M_N	0	0.6
Ta - °F	59.0	-48.0
Pa - psia	14.696	4.364
Rating		
Fn - lb	977	250
SFC - lbm/lbf-h	0.397	0.681
TIT - °F	1940	1780
BPR	5.32	5.22
Win - lbm/s	39.8	19.66
N_1 - rpm	11,660	11,870
N_2 - rpm	35,000	34,320
Pr Compressor	15.52	19.82
Compressor Performance		
Fan:		
Q_{in} - (lbm/s) $\sqrt{°R}$/psia	61.7	74.2
P_r	1.336	1.407
η	0.863	0.862
ΔT - °F	52.0	52.7
IPC:		
Q_{in} - (lbm/s) $\sqrt{°R}$/psia	7.66	8.97
P_r	1.858	2.069
η	0.791	0.797
ΔT - °F	139.1	143.1
HPC:		
Q_{in} - (lbm/s) $\sqrt{°R}$/psia	4.600	4.924
P_r	6.251	6.806
η	0.744	0.749
ΔT - °F	626	599
Burner Performance		
Q_{in} - (lbm/s) $\sqrt{°R}$/psia	1.010	1.008
P_r	0.965	0.965
η @ 18,400 Btu/lb	0.995	0.995
Fuel/Air	0.0971	

TABLE XXII. TURBOFAN ENGINE P7808 COMPONENT PERFORMANCE SUMMARY (Sheet 2 of 2) (English)

Turbine Performance		
HP Turbine:		
Q_{in} - (lbm/s) $\sqrt{^{o}R}$/psia	1.427	1.428
P_r	3.496	3.596
η	0.86	0.86
LP Turbine:		
Q_{in} - (lbm/s) $\sqrt{^{o}R}$/psia	4.404	4.511
P_r	3.161	3.573
η	0.86	0.86
$(\Delta P/P)_{BPD}$	0.011	0.015
%(WL/Wcore)	1.0	1.0
CF-Primary	0.982	0.990
CF-Secondary	0.980	C.989

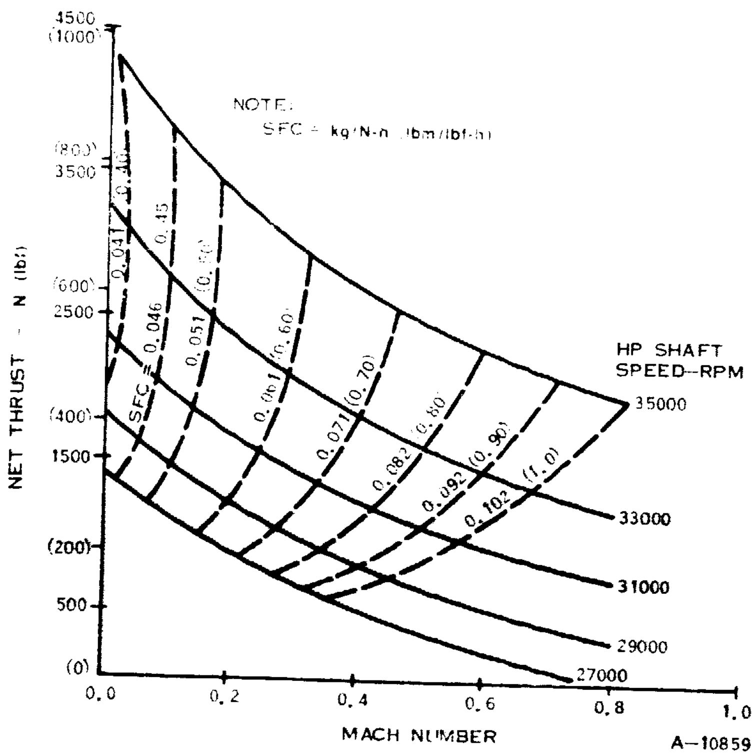


Figure 31. Turbofan Engine P7808 Performance - SL/STD Day

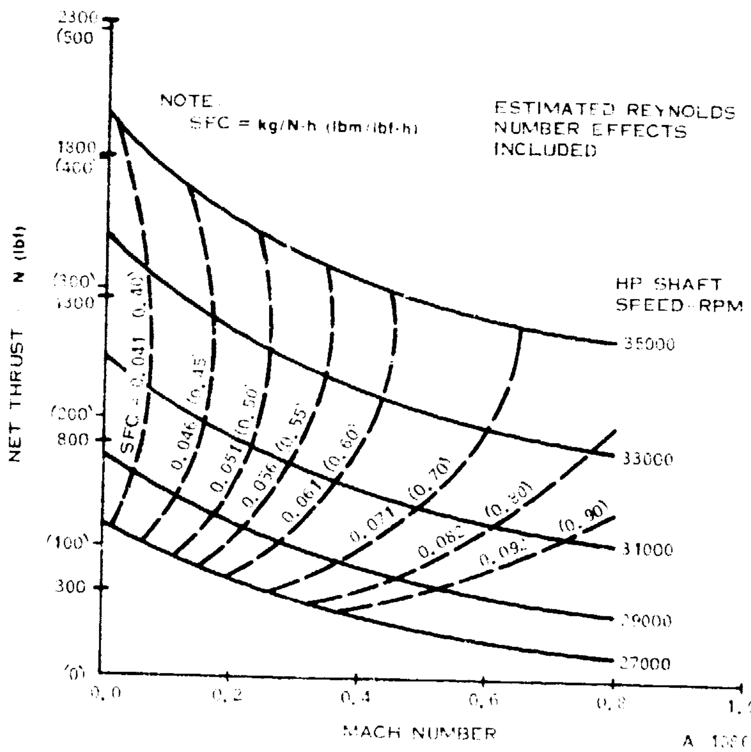
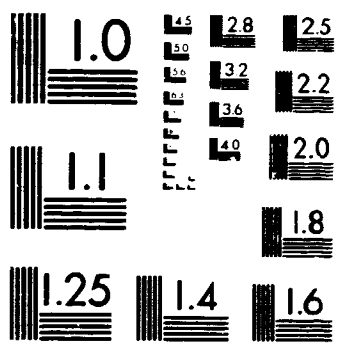


Figure 32. Turbofan Engine P7808 Performance - 9144 m (30,000 ft)/STD Day


1.0
2.8
2.5
3.2
2.2
3.6
4.0
2.0
1.1
1.8
1.25
1.4
1.6

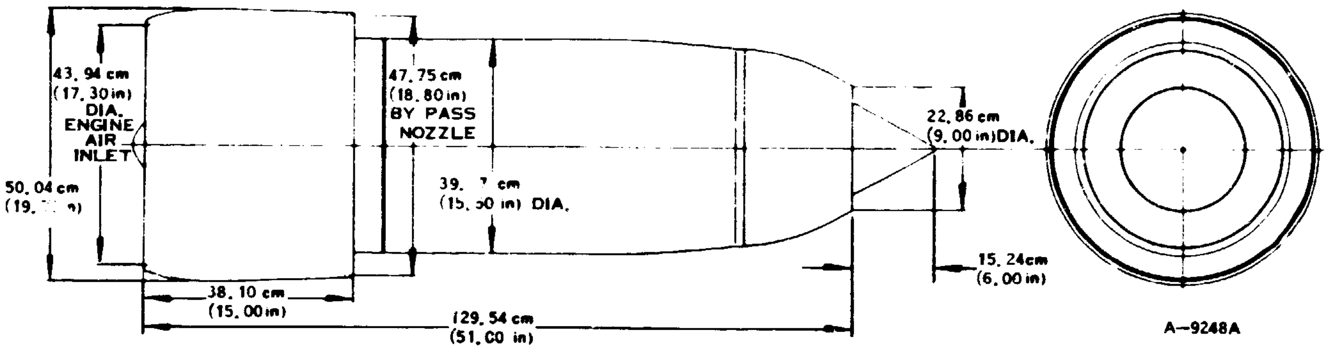


Figure 33. Installation Drawing - Low Cost Conventional Two-Spool Turbofan

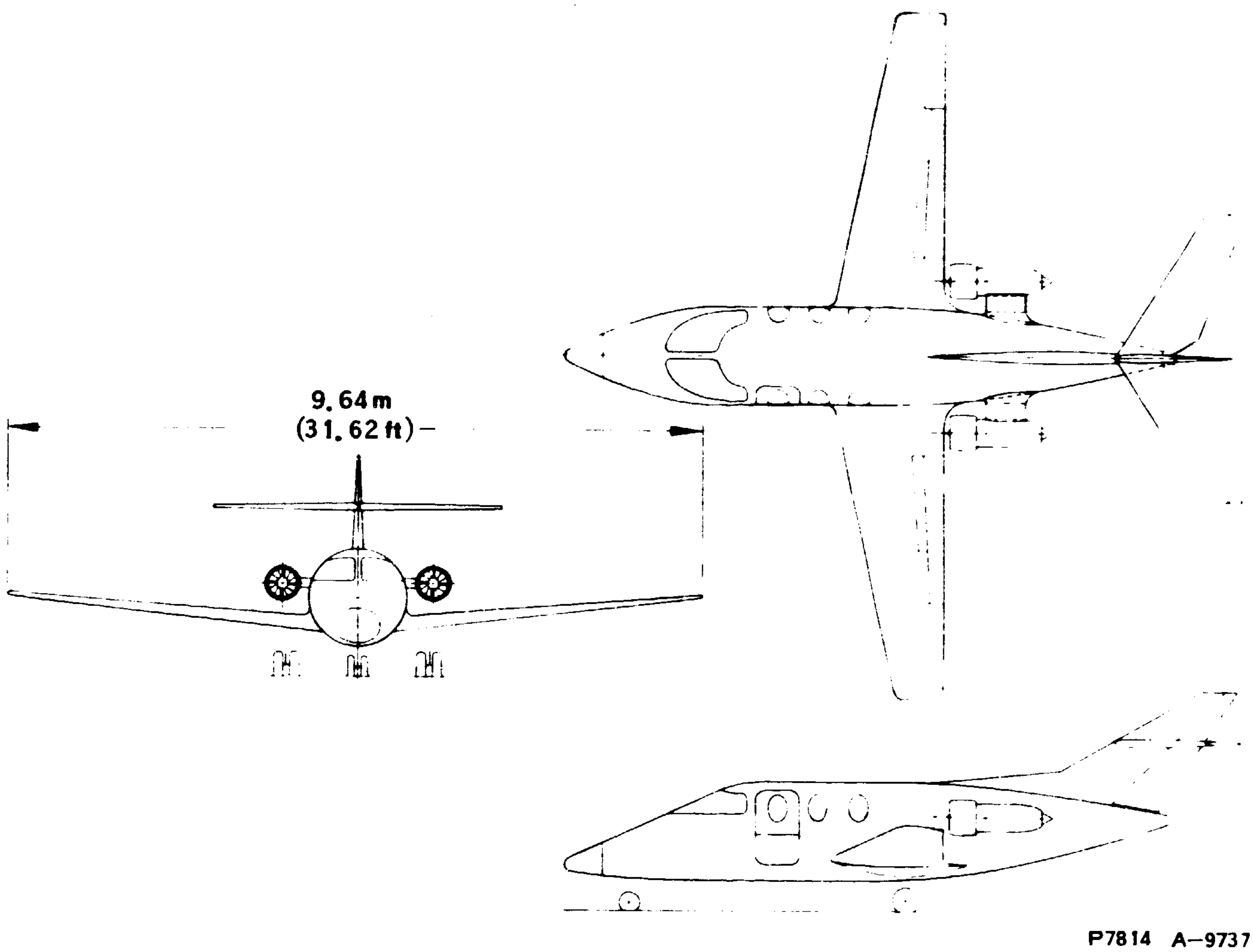


Figure 34. Six-Place Study Airplane with Low Cost Two-Spool Turbofan Engines

TABLE XXIII. TURBOFAN/TURBOPROP/PISTON AIRPLANE PERFORMANCE COMPARISION (GASP)
(SI Units)

AIRPLANE	A-9737 T/F	601P T/P	601P Piston	
Persons on Board	6	6	6	
Gross Weight, kg	2722	2722	2722	
Pressurized, (ΔP), kPa	Yes, (52.4)	Yes, (51.7)	Yes, (29.3)	
Engine	P-7808[1]	P-7757[2]	LYC-IO-540	
Takeoff Rating	4381 N	263 kW	216 kW	
Takeoff Distance (SL, Std Day, GW)				
Ground Run, m	716	309	396	
Over 15.2 m Obstacle, m	1088	532	607	
Rate of Climb (SL, Std Day, GW), m/min	912	780	533	
Time to Climb to 7620 m, min	11.7	15.4	21.8	
Maximum Cruise Speed, km/h	698	537	482	
Service Ceiling (approx), m	12802	10973	8534	
Range (45 min reserve)				
Altitude, m	10973	10668	7620	7620
Range, km	3130	4186	1538	1120
Speed, km/h	583	432	404	443
Max Fuel with 6 on Board, l[3]	1000	931	443	443
km/l	4.03	5.34	4.33	3.80
Seat-km/l	24.2	32.0	26.0	22.8
Landing Distance (SL, Std Day, GW)				
Over 15.2 m Obstacle, m	703	805	805	
Ground Roll, m	457	305[4]	304	

[1]TIT for takeoff and climb = 1339°K. Maximum TIT for cruise = 1283°K. Fuel flow penalty for power extraction and bleed assumed at 3.5%.
[2]TIT for takeoff = 1255°K, for climb = 1228°K, and for cruise = 1200°K maximum. Fuel flow penalty for power extraction and bleed assumed at 4.25%.
[3]Assumes 90.7 kg for each passenger and his baggage.
[4]Can be substantially shortened with reverse thrust.

TABLE XXIII. TURBOFAN/TURBOPROP/PISTON AIRPLANE PERFORMANCE COMPARISION (GASP)
(English)

AIRPLANE	A-9737 T/F	601P T/P	601P Piston	
Persons on Board	6	6	6	
Gross Weight, lbm	6,000	6,000	6,000	
Pressurized, (ΔP), psi	Yes, (7.6)	Yes, (7.5)	Yes, (4.25)	
Engine	P-7808[1]	P-7757[2]	LYC-IO-540	
Takeoff Rating	985 lb	352 hp	290 hp	
Takeoff Distance (SL, Std Day, GW)				
Ground Run, ft	2,349	1,014	1,300	
Over 50 ft Obstacle, ft	3,568	1,746	1,992	
Rate of Climb (SL, Std Day, GW), ft/min	2,991	2,560	1,750	
Time to Climb to 25,000 ft, min	11.7	15.4	21.8	
Maximum Cruise Speed, knots	377	290	260	
Service Ceiling (approx), ft	42,000	36,000	28,000	
Range (45 min reserve)				
Altitude, ft	36,000	35,000	25,000	25,000
Range, nm	1,690	2,260	830	605
Speed, knots	315	233	218	239
Max Fuel with 6 on Board, gal[3]	264	246	117	117
nm/gal	8.23	10.92	8.86	7.77
Seat-nm/gal	49.4	65.5	53.2	46.6
Landing Distance (SL, Std Day, GW)				
Over 50 ft Obstacle, ft	2,305	2,642	2,640	
Ground Roll, ft	1,500	1,000[4]	997	

[1]TIT for takeoff and climb = 1950°F. Maximum TIT for cruise = 1850°F. Fuel flow penalty for power extraction and bleed assumed at 3.5%.
[2]TIT for takeoff = 1800°F, for climb = 1750°F, and for cruise = 1700°F maximum. Fuel flow penalty for power extraction and bleed assumed at 4.25%.
[3]Assumes 200 lbm for each passenger and his baggage
[4]Can be substantially shortened with reverse thrust.

TABLE XXIV. TURBOFAN/TURBOPROP/PISTON WEIGHT BREAKDOWN COMPARISON (GASP DATA)

AIRPLANE COMPONENT/GROUP	A-9737 T/F		601P T/P		601P Piston	
	kg	lbm	kg	lbm	kg	lbm
Propulsion Group						
Primary Engines	168	370	161	354	504	1112
Primary Engine Installation	36	80	45	100	96	211
Fuel System	27	59	30	67	15	32
Propulsor Weight	0	0	82*	180*	86	190
Total Propulsion Group Weight	231	509	318	701	701	1545
Structures Group						
Wing	226	498	261	576	261	576
Horizontal Tail	42	92	33	72	32	71
Vertical Tail	28	62	17	37	16	36
Fuselage	340	749	239	528	228	502
Landing Gear	87	191	122	270	122	269
Primary Engine Section	34	76	52	114	127	280
Total Structures Group Weight	756	1667	725	1598	786	1734
Flight Controls Group						
Cockpit Controls	10	23	10	23	10	23
Fixed Wing Controls	39	87	40	88	35	77
Total Controls Group Weight	49	110	50	111	45	100
Weight of Fixed Equipment	291	641	291	641	291	641
Weight Empty	1327	2927	1384	3051	1823	4020
Fixed Useful Load (Inc. Crew of 1)	125	275	125	275	125	275
Operating Weight Empty	1452	3202	1509	3326	1948	4295
Payload	454	1000	454	1000	454	1000
Fuel	816	1798	759	1674	320	705
Gross Weight	2722	6000	2722	6000	2722	6000

* 1988 Technology propellers (composite blades) assumed.

Drag buildup data for the three airplanes are compared in Table XXV.

ENGINE-RELATED LIFE CYCLE COSTS (LCC)

The Mooney and Aerostar turboprop retrofit studies show that the retrofitted airplanes are competitive with piston-powered counterparts from a fuel efficiency standpoint provided that the turboprop airplanes are flown at altitudes above about 4572 m (15,000 ft). The twin turbofan-powered study airplane is also as fuel-efficient, or more fuel-efficient, than the piston-powered Aerostar for some missions. The "real-world" efficiency advantage derives from the greater ability of the turbofan-powered airplane to surmount frontal weather and fly a straight-line course to the destination.

Fuel efficiency, of course, is only a part of the LCC picture. Engine first cost as well as inspection, maintenance, and overhaul costs are also important. The influence of engine-generated vibration on the airframe and propeller also affect ownership costs.

A limited examination of the foregoing was made using the Mooney, Aerostar, and twin turbofan designs as representative airplanes for determining the viability of the conceptual turbine engines. This was done by calculating turbine and piston engine-related ownership costs over a 20-year period assuming a 185 200 km (100,000 nm) annual airplane utilization rate. Engine-related fleet LCC's were also calculated to enable a comparison of possible turbine-fleet benefits with the investment costs required to develop and certify the P7757 and P7808 turbine engines. In addition to predicting the relative cost impact of introducing nominally-rated turboprop and turbofan engines, cost tradeoffs involving the introduction of higher technology units (i.e., engines with improved aerodynamic components and higher temperature capability) were evaluated.

Several simplifying assumptions were used to facilitate the LCC determinations. Because of these assumptions and the fact that only major cost drivers were considered, the LCC data provided in the present report should be considered "figures of merit" only with the relative values having more meaning than the absolute values. Ground rules, assumptions and costing methodology are discussed in the paragraphs that follow.

LCC Analysis Assumptions

The single-engine Mooney and twin-engine Aerostar were considered representative of the airplane classes where the introduction of an "optimum-type" GATE turboprop engine would be most likely. Although there are numerous other possibilities, these classes were considered typical for individual-airplane and fleet cost analyses, and for turboprop/piston engine-related LCC comparisons. The twin turbofan study airplane was considered typical of the type that could use the P7808 turbofan engine, and it was used as the basis for turbofan LCC analyses. Because there was no piston-powered counterpart for the twin turbofan design, individual-airplane and fleet LCC comparisons were made with the piston-powered Aerostar 601P.

It was assumed that each airplane analyzed would travel 185 200 km (100,000 nm) per year. Also, for computation purposes, a typical trip of 1111 km (600 nm) was assumed. Trip block times and POL (petroleum, oil, and lubricants) usage and cost were calculated using the GASP program for turbine-powered airplanes and flight

TABLE XXV. TURBOFAN/TURBOPROP/PISTON DRAG BUILDUP COMPARISON (GASP DATA)

AIRPLANE	A-9737 T/F[1]	601P T/P[2]	601P Piston[3]
Equivalent Flat Plate Area ($C_{D_o} S_{ref}$)		m^2	
COMPONENT		(ft^2)	
Wing	0.1016 (1.094)	0.1384 (1.490)	0.1314 (1.414)
Fuselage	0.0997 (1.073)	0.1211 (1.303)	0.1160 (1.249)
Vertical Tail	0.0201 (0.216)	0.0145 (0.156)	0.0137 (0.148)
Horizontal Tail	0.0308 (0.332)	0.0380 (0.409)	0.0360 (0.388)
Engine Nacelles	0.0186 (0.200)	0.0344 (0.370)	0.0485 (0.522)
Incremental	0.0035 (0.038)	0 0	0.0248 (0.267)
Total	0.2743 (2.953)	0.3464 (3.728)	0.3704 (3.988)

A-9737 T/F $C_D = 0.0236 + 0.0496\ C_L^2$ ($S_{ref} = 125\ ft^2$)

601P T/P $C_D = 0.0209 + 0.0506\ C_L^2$ ($S_{ref} = 178\ ft^2$)

601P Piston $C_D = 0.0224 + 0.0510\ C_L^2$ ($S_{ref} = 178\ ft^2$)

Flight conditions for Reynolds number and skin friction calculations: (Note: Second iteration runs were not made at speed for best specific range)

[1]A-9737 T/F - M = 0.450 at 10973 m (259 knots at 36,000 ft)

[2]601P T/P - M = 0.400 at 10668 m (231 knots at 35,000 ft)

[3]601P Piston - M = 0.300 at 4572 m (188 knots at 15,000 ft)

manual data for the piston-powered airplanes.* Turbine-engine yearly operating times and associated engine inspection, maintenance, and overhaul frequencies and costs were determined on the basis of trip block times and the number of trips per year (166.7). Because helicopters are used for many tasks where trip mileage has little significance (e.g., cargo transfers using a sling), the turboshaft LCC figures are based on 500 hours per year operation.

An underlying premise for the prediction of GATE-engine life cycle costs is the attainment of a 10,000-hour time between overhaul, a figure consistent with anticipated airframe life. Although attainment of this high a TBO is an ambitious undertaking, it is believed feasible, at least with respect to the proposed turboprop engine, due to the low speed/low stress design characteristic. Many thousands of engineering hours and millions of development dollars will, of course, be required to achieve this goal. For ease of calculating, the 10,000-hour TBO objective was assumed achievable by early production engines planned for introduction at substantially derated power levels in airplanes of the Cougar and Mooney type. The later production, more mature, higher horsepower engines for airplanes like the Aerostar were also assumed to achieve a 10,000-hour TBO.

The 20-year LCC predictions are based on constant year economics (calendar year 1978 dollars). In the case of aviation gas costs, which increased by about ten percent during 1978, mid-1978 costs apply.

LCC Methodology and Predictions

Engine-related life cycle costs were assumed to be influenced by four major cost drivers:

- Initial Investment
- Production Unit Price
- POL
- Inspection, Maintenance and Overhaul

There are, of course, other influences on life cycle cost, but these were not considered for the comparative purposes of the present study.

- Initial Investment

Investment costs were determined through the establishment of a development and certification plan for each turbine-engine type assuming maximum core-engine parts commonality. The initial-investment estimate was made using a "bottoms up" or build-up estimating approach that considered acquisition of production tooling sufficient to meet the annual delivery rates shown in Table XXVI. The estimate was prorated among the various T/P, T/S and T/F applications on the basis of parts commonality and total engines within each category.

*GASP and flight manual performance data can be used synonymously for the piston powered airplanes since GASP airplane performance was made to match flight manual airplane performance.

TABLE XXVI. ANNUAL PRODUCTION QUANTITY ESTIMATES FOR ENGINE PRICING

Turboprop Engines	
• Projected total unit sales per year in 1988 [134-231 kW (180-310 shp) class], Table IX = 13,803	
• Number of units assumed produced annually by one engine manufacturer (used for pricing estimate). (Includes 5137.44 units for single engine applications and 2417.56 units for twin engine applications.)	7,555
Turboshaft Engines	
• Projected total unit sales per year in 1988 [134-746 kw (180-1000 shp) class], Table VIII = 1881	
• Number of units assumed produced annually by one engine manufacturer [134-231 kW (180-310 shp) class] (used for pricing estimate).	620
Turbofan Engines	
• Projected total unit sales per year in 1988 (all thrust levels), Table VIII = 3676	
• Number of units assumed produced annually by one engine manufacturer [4448 N (1000 lbf) thrust class] (used for pricing estimate).	1,115

There were no investment costs associated with the piston engines used for the LCC comparisons because these engines are fully developed and in service.

- Production Unit Price

Production turbine-engine unit prices (equivalent to OEM prices but less product liability insurance allowances) were estimated using the following methodology:

1. Industrial engineering estimates were made of direct labor for fabrication, assembly, and test based on cross sectional drawings of each engine configuration. These estimates were developed in terms of "standard hours," hours that do not consider shop efficiency. Tooling concepts in keeping with relatively high production delivery rates were assumed.

2. Improvement curves were developed for the appropriate quantities, and from these curves variance factors were computed and applied to the standard hours to predict total hours for fabrication, assembly, and test.

3. Manufacturing and engineering support hours and direct cost dollars (i.e., sustaining manufacturing engineering, tool maintenance, inspection, etc.) were estimated using cost estimating relationships (CER's) developed from historical data. These CER's are based on a percentage of fabrication, assembly, and test hours or a percentage of material cost.

4. Once the total direct labor and direct cost dollars (DC$) were projected, a total price was developed using WRC CY 1978 direct labor rates, burden rates typical of a production mode, and a profit. Table XXVII summarizes production engine pricing information.

- Petroleum, Oil, and Lubricants (POL)

POL costs were projected by assuming all airplanes would travel 185 200 km (100,000 nm) per year. The stage length of a typical trip was assumed to be 1111 km (600 nm)*, and each trip included 0.2 hr ground maneuvering time. Turbine airplane trip fuel usage was determined using the GASP program and piston airplane fuel usage was calculated from flight manual data where optimum flight profiles could be determined more expeditiously. As already discussed, tests were made of the GASP program to ensure the accuracy of the output.

Fuel costs were based on a survey of prices being charged at local airports in mid-1978. At that time Jet A prices averaged $0.207/liter ($0.784/gal) and 100-octane avgas was priced at $0.227/liter ($0.86/gal). POL costs were based on these figures plus an allowance for oil and lubricants that amounted to $0.005/ liter ($0.02/gal) of Jet A used and $0.008/liter ($0.03/gal) of avgas used. Table XXVIII shows how POL costs were determined for the twin turbofan study airplane. Table XXIX gives an example of the methodology used to determine the 20-year fleet

*The most recent nationwide survey conducted by the FAA and the Civil Air Patrol indicated the average stage length of all business-use jet aircraft to be 891 km (481 nm). Piston and turboprop airplane stage lengths can be expected to be less. The 1111 km (600 nm) assumption was made with the expectation that, because of the energy situation, short range, inefficient flights (that lower the stage-length average) will be curtailed in 1988.

TABLE XXVII. PRODUCTION ENGINE PRICING

Production unit prices are based on:

- Industrial Engineering estimates of direct labor and material/subcontract dollars using preliminary cross-sectional drawings for each engine
- Direct labor and burden rates based on an LCC study for a similar direct labor base. Prices are expressed in terms of CY 1978 dollars.
- Projected engine quantities are for a 20-year time period using a 20 percent-per-year build-up rate until the maximum annual production rate shown in Table XXVI is reached. The rate then remains constant for the subsequent 15 years.

The theoretical price of the first production unit and the average production unit price for each engine type are shown below:

Engine Type	Price of First Unit	Average Production Price Per Unit	Number of Units At Lot Midpoint
Turboprop	$23,000	$19,515	67,995
Turboshaft	35,000	26,163	5,580
Turbofan	40,100	25,352	10,035

TABLE XXVIII. METHODOLOGY FOR DETERMINING PETROLEUM/OIL/LUBRICANTS (POL) USE, TWIN TURBOFAN STUDY AIRPLANE P7814

Flight Condition	Fuel Used[1]	Time (hrs)[1]
Start, Taxi, Climb to Cruise Altitude	121.74 kg (268.4 lbm)[149.41 l(39.47 gal)]	0.585
Start of Cruise to Landing	185.43 kg (408.8 lbm)[227.58 l(60.12 gal)]	1.629
Totals 1111 km (600 nm)	307.17 kg (677.2 lbm)[376.99 l(99.59 gal)]	2.214
Flights/Year	= 185 200 km (100,000 nm)[2] / 1111 km (600 nm)[3]	= 166.67 Flights
Fuel/Year	= (gal/flight) x FFCF[4] x flights/year	= 65033 l (17,180 gal)
Fuel/Year/Engine		= 32517 l (8,590 gal)
POL priced at $0.212/l ($0.804/gal) Assume Jet "A" @ $0.207/l + $0.005 ($0.784/gal + $0.02) allowance for oil and lubricants (applicable to turboprop and turbofan).		
POL Cost/Year/Engine	= $ 6,906	
Total POL Cost/Engine for 20-year Operation	= $138,120	

[1]Computed using the NASA GASP computer program with WRC inputs for airplane and engine characteristics.

[2]Assumed average flight kilometers (nautical miles) per year.

[3]Assumed average flight kilometers (nautical miles) per trip.

[4]Fuel flow correction factor for power extraction and bleed air (1.035 for turbofan, 1.0425 for turboprop).

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TABLE XXIX. METHODOLOGY FOR DETERMINING 20-YEAR TURBOPROP FLEET POL COSTS

Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Total
Annual Prdctn Factor	0.2	0.4	0.6	0.8	1.0																18
Eng Fielding Factor	0.2	0.6	1.2	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	172

Airplane	Engine: T/P Engines Produced Annually (see Table XXVI) ①	Engine: Type of Components*	Engine: TIT*	ESFC Ratio* ②	Annual POL Cost, Nominal Eng ③	20-year POL Cost x 10^{-9} 172 x ① x ② x ③
S.E. T/P	5137	nominal	nominal	1.000	\$5631	\$4.97
S.E. T/P	5137	nominal	improved	0.937	5631	4.66
S.E. T/P	5137	improved	nominal	0.902	5631	4.48
S.E. T/P	5137	improved	improved	0.861	5631	4.29
T.E. T/P	2418	nominal	nominal	1.000	\$5167	\$2.15
T.E. T/P	2418	nominal	improved	0.937	5167	2.01
T.E. T/P	2418	improved	nominal	0.902	5167	1.94
T.E. T/P	2418	improved	improved	0.861	5167	1.85

*See Table XLIII for turboprop component efficiency and TIT definitions. ESFC ratios were also obtained from Table XLIII.

fuel cost figures and summarizes the cumulative totals for the turboprop airplanes involved in the LCC comparisons. Note that the engine fielding factor is an index of the total number of engines in the field assuming no engine retirements.

- Inspection, Maintenance, and Overhaul

Mooney 201 and Aerostar 601P piston airplane inspection, maintenance and overhaul costs were obtained from manufacturer-supplied data. For the Mooney, piston engine-related inspection and maintenance costs were assumed to equal one-half of the airframe-plus-engine figure. The fraction for the twin-engine Aerostar was assumed to be two-thirds. Shop labor rates were adjusted upward to $20.00/hr for consistency and to match turbine-airplane shop labor rates. The assumption of equal turbine/piston shop labor rates is believed reasonable in the light of a circa-1988 market scenario for general aviation wherein turbine-powered airplanes are assumed to dominate the fleet additions. Tables XXX and XXXI show the cost data supplied by Mooney and Piper and the adjustments made to this data to arrive at a yearly allowance for piston-engine inspection, maintenance, and overhaul.

An underlying premise in projecting the life cycle costs for the turbine-engines is the achievement of a TBO of the order of that of the airframe (10,000 hours assumed). At a travel rate of 100,000 nm per year for each year of the 20-year LCC study, the twin-engine, turbine-powered airplanes would accumulate less than 10,000 hours. The turboprop-powered Mooney would accumulate about 13,000 hours when flown with a derated powerplant. Because no engine can be expected to run flawlessly for 20 years without some kind of parts replacement, a contingency reserve was set aside to permit the replacement of deteriorated parts and parts damaged by foreign objects. This reserve is sufficient to permit one complete engine replacement in 20 years and it has been prorated over this period.

Specific inspection and maintenance actions as well as associated frequencies were identified for each turbine-engine type. With the exception of occasional filter and igniter plug replacements, the proposed engines were considered relatively maintenance-free. An isotope inspection was included at 500-hour intervals to verify the absence of cracking or other deleterious conditions in critical parts. A list of the specific maintenance actions identified and the corresponding cost estimates are given in Tables XXXII and XXXIII. Twenty-year piston- and turbine-fleet inspection, maintenance, and overhaul cost summations are provided in Tables XXXIV through XLII. These summations were made using the engine fielding factor described in Table XXIX.

Turbine/Piston LCC Comparisons

In order to get at the cost benefits, if any, of going to turbine power, the direct operating cost (DOC) and engine production cost estimates previously discussed were combined and piston/turbine cost comparisons made. The 20-year summations were based on 20 percent per year turbine-engine production build-up rates to the predicted peak values shown in Table XXVI. Thereafter, the annual production rates were assumed constant at the peak values. The engine-related cost predictions were made on the basis of the total engine population in the particular year of interest.

As an additional aid for evaluating the monetary and fuel economy implications of a general aviation industry movement toward the expanded use of turbine powerplants, information of the following type has also been provided in the LCC summaries:

TABLE XXX. ENGINE-RELATED INSPECTION, MAINTENANCE, AND OVERHAUL COSTS
PISTON MOONEY 201

Airplane Manufacturer Data	$ Per Operating Hour
• Airframe and Engine Inspection and Maintenance (includes a small allowance for parts replacement)	3.48
• Engine Overhaul (O/H) Allowance	3.13
Adjusted Data*	
• Engine Inspection and Maintenance (assumes engine-related inspection and maintenance cost equals approximately one-half of airframe-plus-engine figure) 0.5 x \$3.48 x (20/13) = \$2.68	2.68
• Engine O/H Allowance (assumes field O/H) \$3.13 x (20/13) = \$4.81	4.81
Total Engine Maintenance and O/H Allowance	\$7.49/hr
Yearly Allowance for Engine Inspection, Maintenance, and O/H	\$5063
• $\frac{\text{185 200 km/yr (100,000 nm/yr)}}{\text{274 km/h (148 knots)}}$ = 676 hr/yr 676 x \$7.49 = \$5063	

*Manufacturer data based on \$13/hr for shop labor. This figure adjusted to \$20/hr for consistency with shop labor rates applicable to turbine-powered aircraft (equal piston/turbine labor rates assumed for 1988).

TABLE XXXI. ENGINE-RELATED (ONE ENGINE) INSPECTION, MAINTENANCE, AND OVERHAUL COSTS - PISTON AEROSTAR 601P

Item	$ Per Operating Hour
Airplane Manufacturer Data	
• Airframe and Engine Inspection and Maintenance (includes $1.00 allowance for propeller and governor O/H)	$13.00
• Engine Exchange Allowance (two factory remanufactured engines)	12.01
Adjusted Data*	
• Inspection, Maintenance and Propeller/Governor O/H $13.00 x (20/15) = $17.33	17.33
• Less Propeller/Governor O/H $1.00 x (20/15) = $1.33	- 1.33
Airframe and Engine Inspection and Maintenance	$16.00/hr
• Engine Inspection and Maintenance (assumes engine-related inspection and maintenance cost equals two-thirds the airframe-plus-engine figure) 0.667 x $16.00 = $10.67	
• Inspection and Maintenance Cost Per Engine = 0.5 x $10.67	$ 5.33/hr
Yearly Engine-Related Inspection and Maintenance Cost	$2448
• $\frac{185200 \text{ km/yr } (100,000 \text{ nm/yr})}{403 \text{ km/hr } (218 \text{ knots})} = 459$ hr/yr 459 hr/yr x $5.33/hr = $2448	
Engine Exchange Allowance (one engine)	$2759
• 459 hr/yr x 0.5 x $12.01/hr = 2759 (adjustment for factory labor rate not required)	
Yearly Allowance for Engine and Propeller Inspection, Maintenance, and Overhaul (one engine)	$5207
$2448 + $2759 = $5207	

*Manufacturer data based on $15/hr for shop labor. This figure adjusted to $20/hr for consistency with shop labor rates applicable to turbine-powered aircraft (equal piston/turbine labor rates assumed for 1988).

TABLE XXXII. TURBINE-ENGINE SCHEDULED INSPECTION AND MAINTENANCE COST

Scheduled Maintenance Event	Frequency (hr)	Estimated Manhours	Parts Costs, $
Oil, Oil Filter and Fuel Filter (replace oil and clean or replace filters as required)	100	0.8	35
Check Igniter Plugs (replace at 500-hr)	100	0.5	2 x 265
Inspect Wiring, Tubing, Connections, and Screws	100	0.5	--
Chip Detector (inspect and clean as necessary)	100	0.5	--
Isotope Inspection	500	1.5	75
	100-hr total	2.3	$ 35
	500-hr total	3.8	$640

Assume Shop Labor Cost = \$20/hr
Cost of 100-hr Inspection = 2.3 x \$20 + \$35 = \$81
Cost of 500-hr Inspection = 3.8 x \$20 + \$640 = \$716
Average Hourly Inspection Cost = (\$81 x 4 + \$716)/500 = \$2.08

TABLE XXXIII. TURBINE-ENGINE INSPECTION AND MAINTENANCE COST

Average Hourly Scheduled Inspection and Maintenance Cost = $2.08

Eng Application & Type	Component Efficiency*	TIT*	Engine Cost ($)	Hr/Yr	20-Yr Insp & Main. Cost ($)	20-Yr Cost + Engine Rplmnt Contingency ($)	1-Yr Main. Cost Accrual/Eng** ($)	Hourly Main. Cost Accrual/Eng ($)
S.E. Turboprop	nominal	nominal	19,515	641	26,666	46,181	2,309	3.60
S.E. Turboprop	improved	nominal	19,515	641	26,666	46,181	2,309	3.60
S.E. Turboprop	nominal	improved	21,466	641	26,666	48,132	2,407	3.76
S.E. Turboprop	improved	improved	21,466	641	26,666	48,132	2,407	3.76
T.E. Turboprop	nominal	nominal	19,515	479	19,926	39,441	1,972	4.12
T.E. Turboprop	improved	nominal	19,515	479	19,926	39,441	1,972	4.12
T.E. Turboprop	nominal	improved	21,466	479	19,926	41,392	2,070	4.32
T.E. Turboprop	improved	improved	21,466	479	19,926	41,392	2,070	4.32
T.E. Turbofan	nominal	nominal	25,352	369	15,350	40,702	2,035	5.51
T.E. Turbofan	improved	nominal	25,352	369	15,350	40,702	2,035	5.51
T.E. Turbofan	nominal	improved	27,887	369	15,350	43,237	2,162	5.86
T.E. Turbofan	improved	improved	27,887	369	15,350	43,237	2,162	5.86
Turboshaft	nominal	nominal	26,163	500	20,800	46,963	2,348	4.70
Turboshaft	improved	nominal	26,163	500	20,800	46,963	2,348	4.70
Turboshaft	nominal	improved	28,768	500	20,800	49,568	2,478	4.96
Turboshaft	improved	improved	28,768	500	20,800	49,568	2,478	4.96

*See Tables XLIII through XLV for component efficiency and TIT definitions
**Includes contingency reserve

TABLE XXXIV. TWENTY-YEAR TURBOPROP/PISTON LCC COMPARISON - NOMINAL COMPONENTS, NOMINAL TIT

Major LCC Category	Single Engine Application[1]		Twin Engine Application[2]	
	Turboprop	Piston	Turboprop	Piston
Initial Investment, $	27,721,763[3]	N/A	13,045,183[3]	N/A
Total Engine Quantity	92,474	92,474	43,516	43,516
Production Engine Price, $				
Unit	19,515	6,447	19,515	13,620
Total	1,804,630,110	596,179,878	849,214,740	592,687,920
POL Cost[4], $	4,975,779,343	5,015,543,163	2,148,539,644	2,921,964,017
Maintenance/Overhaul[5], $	2,040,325,786	4,473,871,570	819,996,164	2,165,172,426
Total Cost through Operating Period, $	8,820,735,239	10,085,594,611	3,817,750,548	5,679,824,363
20-year LCC/Engine[6], $	178,315	221,227	162,295	258,300
$/Seat-km (seat-nm)/Airplane (engine-related only)	0.012(0.022)	0.015(0.028)	0.015(0.027)	0.023(0.043)
km (nm) Traveled/Year	185200(100,000)	185200(100,000)	185200(100,000)	185200(100,000)
l (gal) Fuel/Year/Airplane	26513(7,004)	24143(6,378)	48655(12,853)	59775(15,791)

[1]Mooney 201.
[2]Aerostar 601P.
[3]Same engine, investment costs prorated between single and twin applications (approx $300/eng).
[4]See Table XXIX.
[5]See Tables XXVI and XXXIII. Cost = 172 ($/yr/eng) (engines produced annually).
[6]20-yr turbine LCC/eng = initial cost + 20 x annual POL $ + 20 x annual maintenance $.

TABLE XXXV. TWENTY-YEAR TURBOPROP/PISTON LCC COMPARISON - IMPROVED COMPONENTS, NOMINAL TIT

Major LCC Category	Single Engine Application[1]		Twin Engine Application[2]	
	Turboprop	Piston	Turboprop	Piston
Initial Investment, $	29,071,972[3]	N/A	13,680,558[3]	N/A
Total Engine Quantity	92,474	92,474	43,516	43,516
Production Engine Price, $				
Unit	19,515	6,447	19,515	13,620
Total	1,804,630,110	596,179,878	849,214,740	592,687,920
POL Cost[4], $	4,485,993,457	5,015,543,163	1,937,050,283	2,921,964,017
Maintenance/Overhaul[5], $	2,040,325,786	4,473,871,570	819,996,164	2,165,172,426
Total Cost through Operating Period, $	8,330,949,353	10,085,594,611	3,606,261,187	5,679,824,363
20-year LCC/Engine[6], $	167,229	221,227	152,123	258,300
$/Seat-km (seat-nm)/Airplane (engine-related only)	0.011(0.021)	0.015(0.028)	0.014(0.025)	0.023(0.043)
km (nm) Traveled/Year	185200(100,000)	185200(100,000)	185200(100,000)	185200(100,000)
l (gal) Fuel/Year/Airplane	23902(6,314)	24143(6,378)	43865(11,588)	59775(15,791)

[1] Mooney 201.
[2] Aerostar 601P.
[3] Same engine, investment costs prorated between single and twin applications (approx. $314/eng).
[4] See Table XXIX.
[5] See Tables XXVI and XXXIII. Cost = 172 ($/yr/eng) (engines produced annually).
[6] 20-yr turbine LCC/eng = initial cost + 20 x annual POL $ + 20 x annual maintenance $.

TABLE XXXVI. TWENTY-YEAR TURBOPROP/PISTON LCC COMPARISON - NOMINAL COMPONENTS, IMPROVED TIT

Major LCC Category	Single Engine Application[1]		Twin Engine Application[2]	
	Turboprop	Piston	Turboprop	Piston
Initial Investment, $	39,185,571[3]	N/A	18,439,770[3]	N/A
Total Engine Quantity	92,474	92,474	43,516	43,516
Production Engine Price, $				
Unit	21,466	6,447	21,466	13,620
Total	1,985,046,884	596,179,878	934,114,456	592,687,920
POL Cost[4], $	4,664,097,415	5,015,543,163	2,013,955,505	2,921,964,017
Maintenance/Overhaul[5], $	2,126,922,550	4,473,071,570	860,746,480	2,165,172,426
Total Cost through Operating Period, $	8,776,066,849	10,085,594,611	3,808,816,441	5,679,824,363
20-year LCC/Engine[6], $	175,172	221,227	159,733	258,300
$/Seat-km (seat-nm)/Airplane (engine-related only)	0.012(0.022)	0.015(0.028)	0.014(0.027)	0.023(0.043)
km (nm) Traveled/Year	185200(100,000)	185200(100,000)	185200(100,000)	185200(100,000)
l (gal) Fuel/Year/Airplane	24851(6,565)	24143(6,378)	45607(12,048)	59775(15,791)

[1]Mooney 201.
[2]Aerostar 601P.
[3]Same engine, investment costs prorated between single and twin applications (approx. $424/engine).
[4]See Table XXIX.
[5]See Tables XXVI and XXXIII. Cost = 172 ($/yr/eng) (engines produced annually).
[6]20-yr turbine LCC/eng = initial cost + 20 x annual POL $ + 20 x annual maintenance $.

TABLE XXXVII. TWENTY-YEAR TURBOPROP/PISTON LCC COMPARISON - IMPROVED COMPONENTS, IMPROVED TIT

Major LCC Category	Single Engine Application[1]		Twin Engine Application[2]	
	Turboprop	Piston	Turboprop	Piston
Initial Investment, $	40,535,780[3]	N/A	19,075,145[3]	N/A
Total Engine Quantity	92,474	92,474	43,516	43,516
Production Engine Price, $				
Unit	21,466	6,447	21,466	13,620
Total	1,985,046,884	596,179,878	934,114,456	592,687,920
POL Cost[4], $	4,285,626,503	5,015,543,163	1,850,531,908	2,921,964,017
Maintenance/Overhaul[5], $	2,126,922,550	4,473,871,570	860,746,480	2,165,172,426
Total Cost through Operating Period, $	8,397,595,937	10,085,594,611	3,645,392,844	5,679,824,363
20-year LCC/Engine[6], $	166,605	221,227	151,872	258,300
$/Seat-km (seat-nm)/Airplane (engine-related only)	0.011(0.021)	0.015(0.028)	0.014(0.025)	0.023(0.043)
km (nm) Traveled/Year	185200(100,000)	185200(100,000)	185200(100,000)	185200(100,000)
l (gal) Fuel/Year/Airplane	22837(6,033)	24143(6,378)	41905(11,070)	59775(15,791)

[1]Mooney 201.
[2]Aerostar 601P.
[3]Same engine-investment costs prorated between single and twin applications (approx $438/engine).
[4]See Table XXIX.
[5]See Tables XXVI and XXXIII. Cost = 172 ($/yr/eng) (engines produced annually).
[6]20-yr turbine LCC/eng = initial cost + 20 x annual POL $ + 20 x annual maintenance $.

TABLE XXXVIII. TWENTY-YEAR TURBOSHAFT LIFE CYCLE COSTS

Major LCC Category	Nominal Components Nominal TIT	Improved Components Nominal TIT	Nominal Components Improved TIT	Improved Components Improved TIT
Initial Investment, $	8,365,337	8,776,217	11,853,377	12,264,257
Total Engine Quantity	11,160	11,160	11,160	11,160
Production Engine Price, $				
Unit	26,163	26,163	28,768	28,768
Total	291,979,080	291,979,080	321,050,880	321,050,880
POL Cost[1], $	540,664,800	470,524,502	487,085,405	436,428,523
Maintenance/Overhaul[2], $	250,390,720	250,390,720	264,253,920	264,253,920
Total Cost through Oper Period, $	1,083,034,600	1,012,894,302	1,072,390,205	1,021,733,323
20-year LCC/Engine[3], $	174,523	161,368	169,679	160,179

[1]POL Cost = 172 x ($/yr/eng) x engines produced annually x SFC ratio
= 172 (5070) x 620 x SFC ratio

[2]See Table XXXIII. Cost = 172 x ($/yr/eng) x 620.

[3]Cost = initial cost + 20 x annual POL $ + 20 x annual maintenance $.

TABLE XXXIX. TWENTY-YEAR TURBOFAN/PISTON LCC COMPARISON - NOMINAL COMPONENTS, NOMINAL TIT

Major LCC Category	Twin Turbofan Application	Twin Piston Application[1]
Initial Investment, $	21,227,716	N/A
Total Engine Quantity	20,070	20,070
Production Engine Price, $		
Unit	25,352	13,620
Total	508,814,640	273,353,400
POL Cost[2], $	1,324,432,680	1,347,638,060
Maintenance/Overhaul[3], $	390,272,300	998,598,460
Total Cost through Operating Period, $	2,223,519,620	2,619,589,920
20-year LCC/Engine[4], $	204,172	258,300
$/Seat-km (seat-nm)/Airplane (engine-related only)	0.018(0.034)	0.023(0.043)
km (nm) Traveled/Year	185200(100,000)	185200(100,000)
l (gal) Fuel/Year/Airplane	65030(17,179)	59775(15,791)

[1]Aerostar 601P.

[2]See Tables XXVI and XXVIII. Turbofan POL Cost = 172 x 1115 x 6906.

[3]See Tables XXVI and XXXIII. Turbofan Maintenance/OH Cost = 172 x 1115 x ($/yr/eng).

[4]20-yr turbine LCC/eng = initial cost + 20 x annual POL $ + 20 x annual maintenance $.

TABLE XL. TWENTY-YEAR TURBOFAN/PISTON LCC COMPARISON - IMPROVED COMPONENTS, NOMINAL TIT

Major LCC Category	Twin Turbofan Application	Twin Piston Application[1]
Initial Investment, $	22,254,816	N/A
Total Engine Quantity	20,070	20,070
Production Engine Price, $		
Unit	25,352	13,620
Total	508,814,640	273,353,400
POL Cost[2], $	1,246,524,875	1,347,638,060
Maintenance/Overhaul[3], $	390,272,300	998,598,460
Total Cost through Operating Period, $	2,145,611,815	2,619,589,920
20-year LCC/Engine[4], $	196,047	258,300
$/Seat-km (seat-nm)/Airplane (engine-related only)	0.018(0.033)	0.023(0.043)
km (nm) Traveled/Year	185200(100,000)	185200(100,000)
1 (gal) Fuel/Year/Airplane	61205(16,169)	59775(15,791)

[1]Aerostar 601P.

[2]See Tables XXVI, XXVIII and XLIV. Turbofan POL cost = 172 x 1115 x 6906 x TSFC ratio.

[3]See Tables XXVI and XXXIII. Turbofan Maintenance/OH Cost = 172 x 1115 x ($/yr/eng).

[4]20-yr turbine LCC/eng = initial cost + 20 x annual POL $ + 20 x annual maintenance $.

TABLE XLI. TWENTY-YEAR TURBOFAN/PISTON LCC COMPARISON - NOMINAL COMPONENTS, IMPROVED TIT

Major LCC Category	Twin Turbofan Application	Twin Piston Application[1]
Initial Investment, $	29,947,916	N/A
Total Engine Quantity	20,070	20,070
Production Engine Price, $		
Unit	27,887	13,620
Total	559,692,090	273,353,400
POL Cost[2], $	1,209,518,668	1,347,638,060
Maintenance/Overhaul[3], $	414,628,360	998,598,460
Total Cost through Operating Period, $	2,183,839,118	2,619,589,920
20-year LCC/Engine[4], $	197,263	258,300
$/Seat-km (seat-nm)/Airplane (engine-related only)	0.018(0.033)	0.023(0.043)
km (nm) Traveled/Year	185200(100,000)	185200(100,000)
l (gal) Fuel/Year/Airplane	59388(15,689)	59775(15,791)

[1]Aerostar 601P.

[2]See Tables XXVI, XXVIII and XLIV. Turbofan POL Cost = 172 x 1115 x 6906 x TSFC ratio.

[3]See Tables XXVI and XXXIII. Turbofan Maintenance/OH Cost = 172 x 1115 x ($/yr/eng).

[4]20-yr turbine LCC/eng = initial cost + 20 x annual POL $ + 20 x annual maintenance $.

TABLE XLII. TWENTY-YEAR TURBOFAN/PISTON LCC COMPARISON - IMPROVED COMPONENTS, IMPROVED TIT

Major LCC Category	Twin Turbofan Application	Twin Piston Application[1]
Initial Investment, $	30,975,016	N/A
Total Engine Quantity	20,070	20,070
Production Engine Price,$		
Unit	27,887	13,620
Total	559,692,090	273,353,400
POL Cost[2], $	1,131,610,863	1,347,638,060
Maintenance/Overhaul[3], $	414,628,360	998,598,460
Total Cost through Operating Period, $	2,105,931,313	2,619,589,920
20-year LCC/Engine[4], $	189,138	258,300
$/Seat-km (seat-nm)/Airplane (engine-related only)	0.017(0.032)	0.023(0.043)
km (nm) Traveled/Year	185200(100,000)	185200(100,000)
l (gal) Fuel/Year/Airplane	59035(15,595)	59775(15,791)

[1]Aerostar 601P.

[2]See Tables XXVI, XXVIII and XLIV. Turbofan POL cost = 172 x 1115 x 6906 x TSFC ratio.

[3]See Tables XXVI and XXXIII. Turbofan Maintenance/OH Cost = 172 x 1115 x ($/yr/eng).

[4]20-yr Turbine LCC/eng = initial cost + 20 x annual POL $ + 20 x annual maintenance $.

- Life Cycle Cost/Engine
- \$/seat-km (seat-nm)/Airplane (engine-related dollars only)
- Liters (gals) of Fuel/Year/Airplane

Table XXXIV provides 20-year turboprop/piston engine-related LCC comparisons for single- and twin-engine airplane applications, and Table XXXIX provides turbofan/piston LCC comparisons for twin-engine airplane applications only. Nominal turbine engine component efficiencies and turbine inlet temperatures are assumed. Note that turbine engine LCC benefits are exhibited for all applications, while fuel economy benefits are exhibited for the twin-engine turboprop airplane application only.

Because the potential for bettering piston engine economy appeared good for all applications, an investigation was made of the influence of improved turbine engine component efficiencies and turbine inlet temperature capabilities. The following improvement combinations were studied:

- Engines with components having nominal efficiencies and uprated turbine inlet temperature capabilities [Turboprop $\Delta T \simeq 194^{\circ}K$ ($350^{\circ}F$)Turbofan $\Delta T \simeq 145^{\circ}K$ ($260^{\circ}F$)].
- Engines with components having improved efficiencies and nominal turbine inlet temperature capabilities.
- Engines with components having improved efficiencies and uprated turbine inlet temperature capabilities.

Tables XLIII, XLIV and XLV compare the performance of the several engine variants. The estimated impact of the performance improvements on investment requirements, production engine pricing, POL cost, fuel efficiency, etc., is shown in Tables XXXIV through XLII. Note that component efficiency improvements (with or without gains in TIT capability) are sufficient to tilt the turboprop/piston fuel efficiency advantage in favor of the turboprop for the single-engine airplane application. Turbofan TIT gains are required before the twin turbofan study airplane can match the fuel-efficiency of the Aerostar, however.

Airplane Life Cycle Costs

The primary cost impact of introducing turbine engines to airplanes in the under-2722 kg (6000 lb) weight class can be expected to be engine-related. There will be airframe-related cost influences also due to the lessened engine-generated vibrations. The lowered vibration environment will reduce the airframe fatigue cracking and chafing problem common to piston-powered airplanes and prolong the life of controllable propellers and avionics equipment. The potential for additional LCC savings through the introduction of new-design airplanes is good if the designs take advantage of the characteristic light weight and compactness of turbine-engines. The new airplanes can be made smaller, for example, because of the reduced engine weight, cooling drag, and nacelle drag. The lighter, smaller airframes will not require as much propulsive energy and there will be attendant fuel cost benefits.

The higher cost of turbine engines can offset such advantages, however, by influencing airplane insurance costs. The added annual insurance burden can be expected to amount to about two percent of the higher hull value.

It would be a very difficult task for an engine manufacturer to develop a truly meaningful piston/turbine airplane LCC comparison, especially a comparison involving 1988 airframe/avionics/propeller technology, and no attempt has been made here to do this. Some insight along these lines will, perhaps, be obtainable from Beech T-34/T-34C experience after the T-34C has been in the field for several more years.

BENEFITS OF TECHNOLOGY ADVANCEMENTS

Technology advancements which may benefit small engines can be derived from two sources: (1) the technology being developed by the manufacturers of large engines, with or without government support; and (2) technology development programs conducted specifically to benefit small engines. The objectives of currently active large turbine engine programs are shown below:

SUMMARY OF FORECASTED ADVANCED TECHNOLOGY AREAS FOR LARGE TURBOFAN RESEARCH

- Increase turbine entry temperature
- Increase pressure ratio
- Increase bypass ratio
- Increase component performance
  (fan, low-pressure compressor, high-pressure compressor, high-pressure turbine, low-pressure turbine, fan exhaust, core exhaust)
- Noise and emissions reduction
- Accessories improvement
- Variable cycle designs
  (split exhausts and fan flows, variable turbine nozzles)
- Engine life improvement
- Weight reduction
- Cost reduction
- Increased durability

Some of the listed technology areas are formalized and attacked through specific programs, while others of general concern are addressed by all turbine engine manufacturers in order to stay competitive. Some are dealt with through combinations of the foregoing motivations.

While all of these developments are of value to the smaller general aviation turbine, their relative payoff is somewhat different since the utilization of general aviation aircraft is typically much lower than that of airline aircraft. The lower utilization rate puts greater emphasis on first cost relative to operating cost. The specific technology areas that promise the greatest returns for general aviation with respect to the economics of purchasing and operating turbine powered aircraft appear to involve:

- Cost reduction throughout
- Increased component performance (stage efficiencies and turbine work levels)
- Durability improvement and increased life
- Accessory miniaturization and reliability improvement

Programs to increase component performance (particularly compressor and turbine efficiency) and increase the work capability of turbines are worthy candidates for bringing about the operating cost, fuel consumption, and acquisition cost reductions needed to permit the emergence of general aviation turbine engines. An increased turbine work capability, for example, would reduce acquisition cost by reducing the number of turbine stages required for a specific cycle (assuming the maintenance of good efficiency). Alternatively, a more sophisticated cycle could be permitted at the same cost.

Increases in turbine entry temperature benefit turboprop and turboshaft engines by improving both specific output and specific fuel consumption. For these engines, the use of temperatures which demand blade cooling are limited by the increased first cost associated therewith. In certain cases, benefits, such as being able to cover a larger power range with the same basic engine, may justify the expense of developing and producing the small cooled blades. In any event, the turboprop/turboshaft engines will benefit in size, weight, and fuel consumption from any probable increase in temperature which can be attained with only a minor, or zero, cost penalty. Means of increasing TIT which are of interest are: improved materials, better corrosion resistant coatings, lower blade stresses, etc.

In the case of small turbofans, turbine inlet temperature must be considered in relation to pressure ratio and bypass ratio as discussed previously. The optimum temperatures tend to be low enough to permit the use of present state-of-the-art alloys. Use of temperatures above the optimum always increases thrust but at the expense of higher specific fuel consumption. The extraction of blade cooling air further increases specific fuel consumption. In spite of this, the use of cooling may be economically desirable in some cases to permit a given engine design to cover a larger thrust range.

Because of the large difference in size, the cooling techniques presently being utilized in large engines are not directly usable on small engines. Hence, the problem of raising the turbine inlet temperature of small engines will require special attention to develop better alloys and/or coatings or to develop cooling techniques suitable for small blades.

The cycle pressure ratio for a small turbine is a compromise between theoretical thermal efficiency, losses associated with excessively small parts, and the costs arising from additional aerodynamic elements and the increased complexity associated with surge avoidance over the speed range. The last consideration involves both the mechanical complexity of variable vanes and/or blowoff valves and the increased complexity of the system elements to control the variable features. The net result is that small engine pressure ratios will probably fall in the range of 10:1 to 15:1. Such ratios give reasonably good fuel consumption together with a tolerable level of complexity.

The fan bypass ratio of a small turbofan is also a trade-off between a number of factors of which the most important are: cruise specific fuel consumption, engine size and associated external drag, engine weight, engine cost, and sensitivity to inlet and exhaust duct losses. Generally, for cruise speeds of about Mach 0.6, specific fuel consumption is improved by increasing fan bypass ratio for bypass ratios under 8:1. However, increasing the bypass ratio has an undesirable effect on all of the other considerations. An area of particular concern is the interrelation between bypass ratio, permissible fan speed, and low pressure turbine loading. If the complications and expense of a fan drive gear reduction are to be avoided, the low rotational speed required by a high bypass fan to avoid excessive tip speeds results in a requirement for multi-stage low pressure turbine elements. Hence, it is apparent that the development of a moderate temperature rise fan (ΔT = 28° to 45°C) able to tolerate a higher value of WN^2 (W = through flow, N = speed) without an unacceptable loss in efficiency or excessive noise generation would be beneficial.

Improved and reduced cost accessories are needed for small gas turbines, and work toward these ends can be potentially profitable. Accessories such as the fuel control and starter-generator do not scale down in proportion to engine size and this creates weight and nacelle drag penalties on some small turbofan powered airplane designs. The problem could be alleviated by durable, small, high-speed accessories that take advantage of available high rotational shaft speeds. Remote mounting is a second approach, but reliability problems can result.

Fuel control cost and reliability are major areas of concern. The fuel control on a small turbine engine typically costs as much as a new mid-size automobile and contributes from 5 to 15 percent to engine cost. This situation is further complicated by the need for minimum pilot attention since the contemplated aircraft will be mainly operated by a single pilot. A promising avenue for development is an electronic control using state-of-the-art electronic techniques. Problems with this approach are meeting the reliability requirements and attaining sufficient sales volume to justify the nonrecurring expense of the large scale integrated circuits necessary to make the unit cost acceptable.

Another disproportionately expensive item is the starter-generator and its associated drive train. The use of a high speed alternator and rectifier together with an inverter for starting deserves further study and development.

Large engine development work in the following areas has a more or less direct application to small engines.

- Noise reduction and suppression. In the small engine, the frequencies are higher and the acoustic energy is much less but the same principles apply. This knowledge must be applied to make the general aviation turbine socially acceptable.
- Engine life improvements and life cycle cost reductions.

Large engine technology programs oriented toward improving engine life and reducing life cycle costs could benefit small engines from the life extension standpoint. Small engines have problems unique to their size, however, in terms of high specific bearing speeds and an inherently high number of stress cycles due to higher rotational speeds. Bearing, gear, rotor and static structure improvement work, and accessory life increase programs would be attractive.

Large engine work that involves so-called variable cycle designs is now under way. Some of this work could benefit small engines. Because of the more limited operating envelopes of general aviation aircraft, however, the cost of the complex mechanical arrangements probably is not warranted and cannot be offset by fuel saving economies. As noted above, general aviation operations tend to have a lower sensitivity to fuel cost than commercial operations because the annual operating hours are typically lower.

Programs to reduce aircraft engine weight are always important, and this is especially so for small turbofan engines. One of the best locations for mounting turbofans is on the aft fuselage where the plane of rotating parts is behind the cabin pressure bulkhead and the wing fuel tanks. Aft mounting creates airplane weight and balance problems, however, and excessive engine weight aggravates this. On the other hand, weight saving on a small turboprop may be somewhat less important since the turboprop will always weigh less than the piston engine it replaces Furthermore, on single engine airplane designs, the light weight of turboprops sometimes necessitates excessively long nose sections for balance that tend to impair visibility from the cockpit during climb and the landing flare.

The major requirement for small turbine engine marketability is cost reduction Any programs for reducing the cost of large engines should be monitored for their possible applicability to small engines and cost reduction programs specifically aimed at small engines should be undertaken.

Large engine programs to improve resistance to damage from foreign objects such as birds and ice as well as simplified anti-icing schemes must be monitored for possible application to small engines.

In summary, large engine technical and manufacturing developments should be carefully monitored to identify and apply those items which can improve the SFC and weight without increasing cost or which can simplify the engine and reduce its cost. Additionally, programs which are aimed at these same objectives but which are appropriate to the peculiar features of small engines should be vigorously pursued. If both of these things are done, competitive general aviation turbine engines can be anticipated.

SECTION 6

EVALUATION OF THE COMMON CORE CONCEPT

The general aviation field of engine applications consists of approximately 180,000 existing aircraft with 200,000 engine installations and nearly 20,000 annual engine installations in new-production aircraft. By 1988 the total installations are expected to grow to more than 300,000 with a proportionate number of engines coming up for overhaul and replacement. Many owners of engines requiring overhaul would be in the market for a more advanced powerplant that would upgrade the utility of their aircraft if such a unit were available. They would look to turbine power if a cost effective installation were offered. With the potential annual market for new and retrofit turboprop installations at more than 16,000 units, the fielding of a low-cost turbopower engine is feasible if a method can be devised for reducing development and production costs and achieving competitive fuel efficiencies.

If it were possible to use turbopower generators as the core or power source for not just the turboprop (T/P) engines which are potentially so numerous, but also as the critical power core of turboshaft (T/S) and turbofan (T/F) engines, production cost benefits would accrue to all three engine types. The ability to utilize a common core depends on achievement of a design concept which can permit the core to be configured substantially independent of those components, which, by their addition, transform the core into a T/S or T/F engine. Because of the much larger numbers involved in core production for T/P engines, if design compromises are necessary, these compromises should be to the advantage of the T/P engine to assure its acceptance. This consideration introduces difficulties with respect to core thermodynamic cycle optimization.

A well performing T/P engine runs at a fairly high pressure ratio. When the T/P core is converted for use in a T/F engine, the pressure ratio becomes excessive for practical turbine inlet temperatures, i.e., when enough compression is added through the additional stages needed to raise airflow to a value which will produce acceptable thrust levels. By judicious design of the core, however, it is probably possible to provide enough flexibility in compressor geometry and shaft speed to enable a common core to be used as an optimum T/P engine component [224 kW (300 hp) class] as well as the high-pressure section of a T/F engine [4448 N (1000 lbf) thrust class].

A significant aspect of the common core concept is the potential for use of a common set of engine accessories such as fuel pumps, oil pumps, starters, generators, and accessory drives. The accessories constitute a 15 to 30 percent cost fraction of turbine engines, especially of the smaller size engines. If accessories can be made truly common, or only minor modifications are necessary to adapt them to the more complex cycles, a large saving can accrue to the benefit of T/F powerplants.

FAMILY OF ENGINES CONCEPT

General aviation can be decidedly influenced by the availability of high-performance, low-cost propulsion. Low cost is influenced by the requirement for development, non-recurring production, and maintenance or recurring costs. Low development costs are extremely important, as they have a direct bearing on the willingness of business to invest after considering the degree of risk and the expected return. Low production and maintenance costs are important because of the interaction with the production number base and the market sensitivity to maintenance burden. Typical piston engine lifetime maintenance costs can exceed three times acquisition cost. The negative attitude toward high existing maintenance cost could significantly expand the market for low-maintenance engines, thereby improving the rate of return possible. Also, it is unrealistic to assume that high volume production could significantly bring turbine engine costs down, since the national airspace system cannot support such rates.

The low-cost goals of the GATE program require departure from classic turbine design procedures. Several methods can be employed to reduce non-recurring costs in turbine development. One such method is the use of commonality in the design of multiple product lines. The use of parts and assemblies common to several different engines reduces performance and reliability development costs, and common-design manufacturing and assembly procedures introduce further economies. Also, the choice of prototype fabrication methods compatible with low-cost aerodynamic development and low-cost producibility can considerably reduce the cost of achieving objective performance levels by reducing the cost of test and development hardware.

Turbine engines characteristically exhibit high rotational speeds and high temperatures, creating sensitive design parameters (blade stress, disk stress and vibration, shaft dynamics, material properties, control characteristics, shaft suspension, lubrication, tolerances, and quality controls). Reducing the intensity of these design-induced problems permits the development of high-performance, low-speed components using low-cost production methods. Designs for low-cost fabrication must be considered from inception, and these will be far more effective in a low-speed, low-stress environment than in a conventional aircraft gas turbine.

Figure 27 illustrates the high temperature capabilities of some advanced turbine materials and compares them with two commonly used alloys, IN-100 and MAR-M 246. One material that is apparently ideally suited for low-speed, low-stress rotors because of its strength at elevated temperatures and its compatibility with the fabrication techniques being explored for low-cost, dual-property rotors, is designated MA 6000 E. This material lends itself well to blade forging.

Operating costs and fuel economy are also highly important and must be attacked by matching the low-cost components for optimum performance and by developing compatible controls and accessories.

The following pages describe a low-cost set of turbine propulsion systems with a wide range of general aviation aircraft applications (light single-engine turboprops, light and medium twins, helicopters, and small turbofan-powered craft). The engine concepts presented (Figure 35) are a T/P, T/S, and T/F based on a common core and designed around low-speed, low-stress, low-cost approaches.

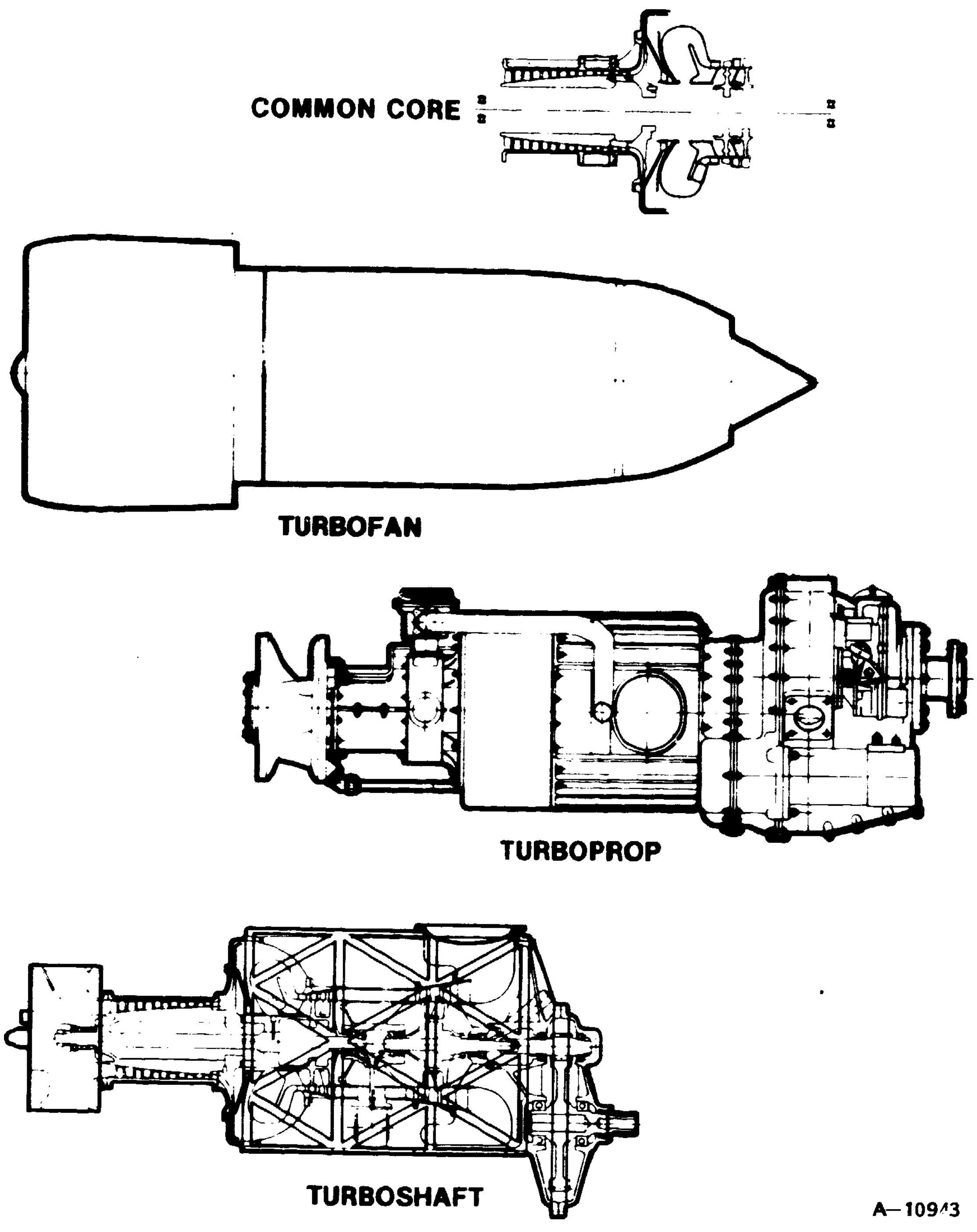

Figure 35. GATE Family of Engines

COMMON CORE CONCEPT DESCRIPTION

The common core concept for this family of engines is a turbine gas generator with the significant parts common to all three engines. As indicated by Figure 36, the major common components are the high-pressure axial compressor, centrifugal compressor, and the turbine.

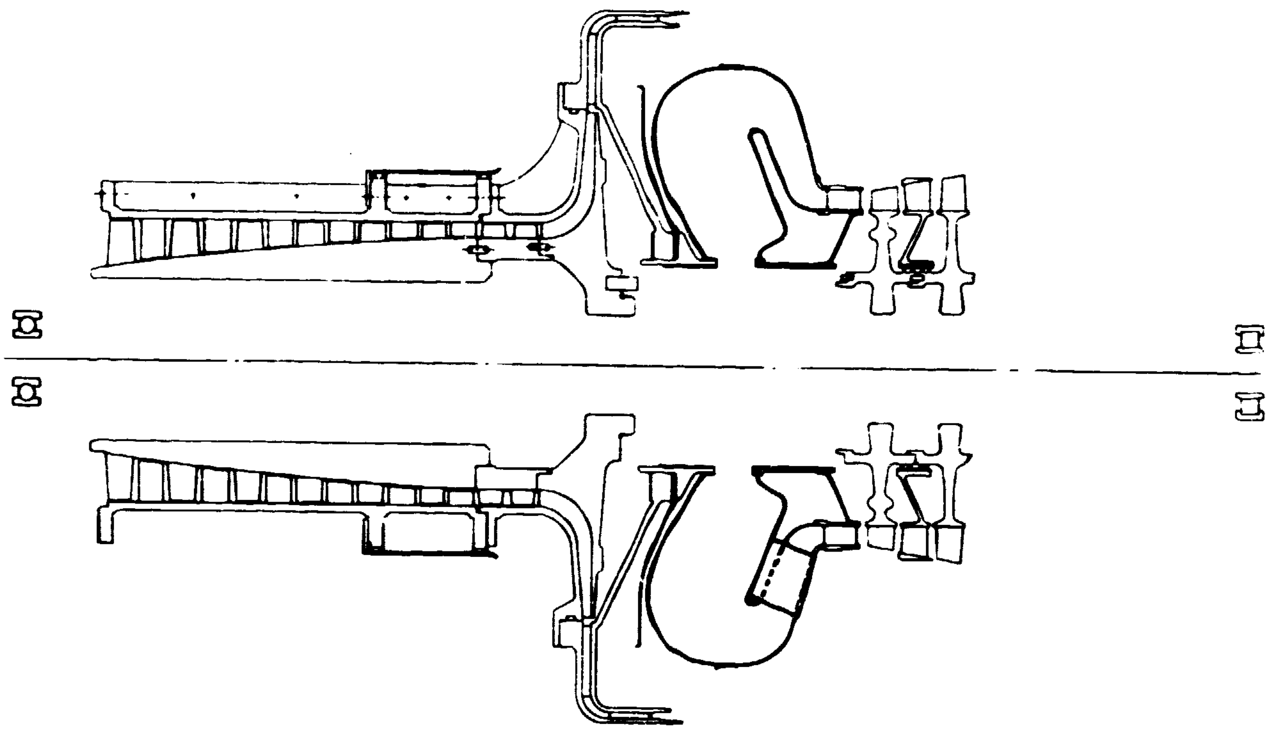

Figure 36. Common Core

The leading element of the high-pressure compressor is a six-stage axial compressor exhibiting approximately a 28°K (50°F) temperature rise per stage at approximately 259 m/s (850 ft/s) tip speed. The axial compressor is designed for low-cost production technology and, as a consequence, has compromised aerodynamic blade configurations. Constant camber, constant twist, and constant blade sections introduce aerodynamic limitations (e.g., via the first stages being set at choke at the tip and stall at the hub, and other blade rows being set aerodynamically at arbitrary incidence).

The axial compressor feeds a centrifugal compressor of relatively low specific speed whose inducer employs a two-stage bladed design planned for manufacture similar to the axial rotor. The radial portion of this design utilizes another low-cost approach wherein blade span and blade numbers are compromised to match the outlet requirement of the axial compressor and overall pressure ratio of 10.3:1 at standard conditions. The radial diffuser is fabricated in accordance with a low-cost concept which regards efficiency and stall margin as design optimization objectives. For fabrication, a shell-molding process involving a no-bake sand molding technique is used.

The high-pressure compressor feeds a combustor designed for fabrication from basic pressed components. Long-life requirements will be achieved by use of thermal barrier coatings and film-cooling techniques. The first stage turbine nozzle will be of relatively conventional configuration but adaptable to a coated and cooled design to achieve long life at increased performance. The turbine rotors and second stage nozzle are of medium-to-low stress design with somewhat compromised blade shapes adaptable to low-cost production methods. Aerodynamic limitations include high taper ratio, non-arbitrary twist, and compromised hub and tip incidence angles and loads.

The core is designed to run at relatively low rotational speeds at standard conditions (as encountered in T/P or T/S applications) and induce relatively low stress and cyclic loads on the rotational parts. This allows simplified, economical bearing and shaft designs. The low initial design speed can be increased for T/F performance optimization. Structures peculiar to the core will be fabricated to be compatible with each engine configuration and the fuel control and starter/generator. These will be designed to allow operation for refinement of aerodynamic, combustion, and mechanical properties. In terms of part costs, the common core components comprise 43.8 percent of the prop and shaft engines and 30 percent of the fan engine.

Preliminary design points for the core components are as follows:

P_r = 10.3 - Compressor Pressure Ratio

η_c = 73 percent - Compressor Efficiency

$\frac{W\sqrt{\theta}}{\delta}$ = 1.59 kg/s (3.50 lbm/s) - Airflow

η_b = 0.99 - Burner Efficiency

η_t = 0.88 - Turbine Efficiency

Significant to the core design is the utilization of a starter/generator compatible with all engine configurations. It is anticipated that the starter/generator will be a hybrid permanent magnet motor/generator of a relatively high-speed brush type. The fuel control contemplated will be an electromechanical type employing a zero-pressure-rise pump metering system controlled by an electronic computer. The design would utilize integrated microcircuits and standard microprocessor modules. This control element for the core would be designed to be compatible for functioning as the primary segment of the control for all three engine types, with enough inherent sophistication to enable its adaptation to the range of control functions required for each application.

TURBOPROP ENGINE DESCRIPTION

The conceptual design of the T/P engine shown in Figure 37 is basically a 224/298 kW (300/400 hp), flat-rated, fixed-shaft turbine. It is designed for medium performance at very low production cost. The fixed-shaft concept was chosen

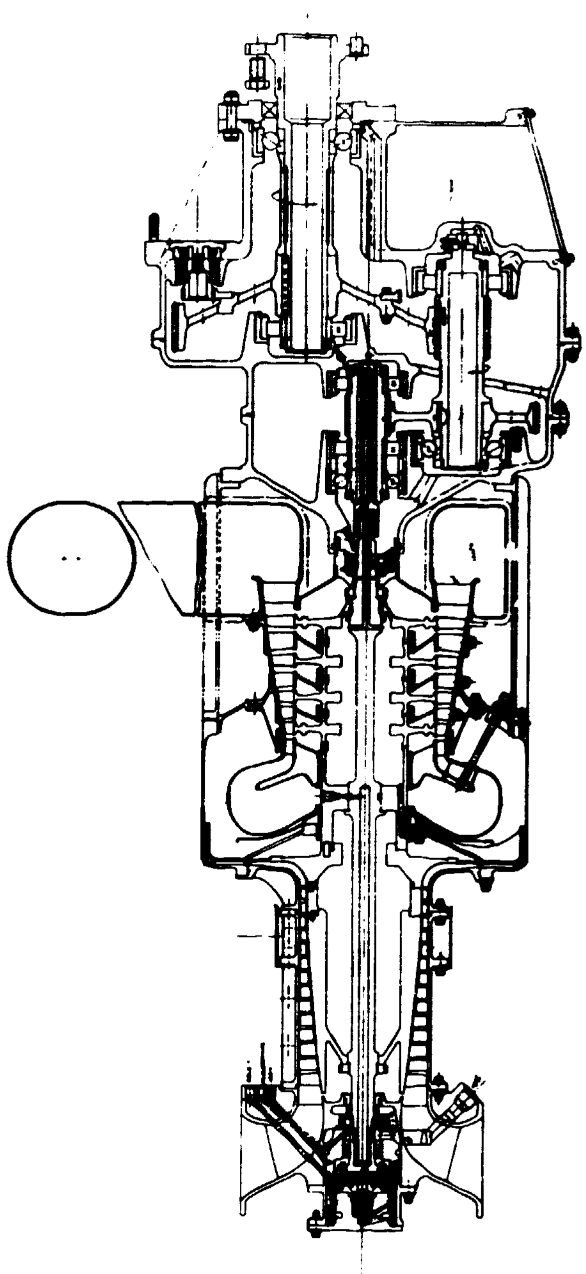

Figure 37. Turboprop Engine

because it is approximately one-third lower in cost than free turbine designs and is compatible with lower cost control systems. The constant speed characteristics of engine operation tend to reduce problems of supplying electrical power and bleed air for cabin pressurization. Also, the engine response is faster in landing modes due to the fixed-shaft design, and this enhances go-around capability as compared to free-turbine-powered airplanes. The turboprop's predicted performance is shown for two levels of component efficiency and two turbine inlet temperature levels in Table XLIII.

The engine consists of a gas generator composed of the compressor and burner elements described previously in the common core account. Two stages are added to the turbine section for power delivery and a simple single-shaft power reduction gearbox is incorporated for propeller drive. The engine is designed to run at low rotational speed and low stress levels, both in the compressor and turbine. This low rotational speed simplifies the gearbox, which is designed to benefit from low-cost manufacturing processes.

The engine is designed with the inlet at the rear and the exhaust directly behind the propeller reduction gearbox. This geometry eases the problems of foreign object ingestion, induction system icing, distortion, noise, accessory access for service, and installation in single-engine and some twin-engine airplanes.

The compressor blading and drum material will be titanium. Predicted engine weight is 73 kg (160 lbm) without starter/generator but with all other equipment including control system and interstage bleed valve [80 kg (177 lbm) with starter-generator]. All gears will employ powdered metal fabrication technology.

TABLE XLIII. LOW COST TURBOPROP PERFORMANCE SUMMARY AT MAXIMUM RATING (UNINSTALLED)*
(SI Units)

Component Efficiency Level	Nominal		Nominal		Improved		Improved	
Turbine Inlet Temperature Level	Nominal 1283°K		Improved 1478°K		Nominal 1283°K		Improved 1478°K	
Altitude - m	0	7620	0	7620	0	7620	0	7620
Flight Velocity - km/h	0	519	0	519	0	519	0	519
Ambient Temp - °K	288	238.6	288	238.6	288	238.6	288	238.6
Shaft Output Power - kW	280.2	189.6	432.3	277.8	357.9	233.9	531.5	335.7
Net Thrust - N	356.3	133.0	363.0	138.8	396.3	149.5	395.4	149.9
Fuel Flow - kg/h	102.6	58.1	138.8	77.2	112.9	63.9	152.1	84.9
Engine Inlet Airflow - kg/s	1.59	0.84	1.59	0.85	1.74	0.93	1.74	0.94
Shaft Speed - rpm	35,000	35,000	35,000	35,000	35,000	35,000	35,000	35,000
Exhaust Gas Temp - °K	824	786	960	916	799	763	932	889
BSFC - kg/kW-h	0.366	0.307	0.321	0.278	0.316	0.273	0.286	0.253
ESFC - kg/kW-h	0.338	0.272	0.304	0.255	0.294	0.245	0.273	0.234
Compressor (Overall)								
Pr	10.33	12.84	10.35	12.83	11.34	14.08	11.34	14.708
η_c	0.734	0.725	0.733	0.724	0.770	0.763	0.781	0.772
Turbine (Overall)								
Pr	8.53	10.81	8.64	11.04	9.28	11.71	9.454	11.992
η_t	0.883	0.881	0.878	0.875	0.903	0.900	0.897	0.894

*Assumed losses - 1.5% gearbox, 1.119 kW parasitic

TABLE XLIII. LOW COST TURBOPROP PERFORMANCE SUMMARY AT MAXIMUM RATING (UNINSTALLED)*
(English)

Component Efficiency Level	Nominal		Nominal		Improved		Improved	
Turbine Inlet Temperature Level	Nominal 1850°F		Improved 2200°F		Nominal 1850°F		Improved 2200°F	
Altitude - (ft)	0	25,000	0	25,000	0	25,000	0	25,000
Flight Velocity - (knots)	0	280	0	280	0	280	0	280
Ambient Temp - °F	59	-30.2	59	-30.2	59	-30.2	59	-30.2
Shaft Output Power - hp	375.7	254.3	579.7	372.6	479.9	313.6	712.8	450.2
Net Thrust - lb	80.1	29.9	81.6	31.2	89.1	33.6	88.9	33.7
Fuel Flow - lb/hr	226.1	128.1	305.9	170.3	248.9	140.8	335.4	187.1
Engine Inlet Airflow - lb/sec	3.50	1.86	3.50	1.865	3.84	2.05	3.84	2.079
Shaft Speed - rpm	35,000	35,000	35,000	35,000	35,000	35,000	35,000	35,000
Exhaust Gas Temp - °F	1024	956	1268	1190	979	913	1218	1140
BSFC - lb/hp-hr	0.602	0.504	0.528	0.457	0.519	0.449	0.471	0.416
ESFC - lb/hp-hr	0.555	0.447	0.500	0.419	0.483	0.403	0.448	0.385
Compressor (Overall)								
Pr	10.33	12.84	10.35	12.83	11.34	14.08	11.34	14.078
η_c	0.734	0.725	0.733	0.724	0.770	0.763	0.781	0.772
Turbine (Overall)								
Pr	8.53	10.81	8.64	11.04	9.28	11.71	9.454	11.992
η_t	0.883	0.881	0.878	0.875	0.903	0.900	0.897	0.894

*Assumed losses - 1.5% gearbox, 1.5 hp parasitic

TURBOSHAFT ENGINE DESCRIPTION

The conceptual design of the T/S engine shown in Figure 38 is a free turbine with the aerodynamics of the gas generator basically identical to that of the common core but with a free turbine driving a simple 6,000 rpm output gearset and a high-speed accessory drive. A compressor bleed valve is provided at the aft end of the axial component to avoid surge problems under part-speed conditions. The fuel control is a version of the common core control with features added for free turbine overspeed protection. The starter/generator would be the same as for the T/P engine with similar performance.

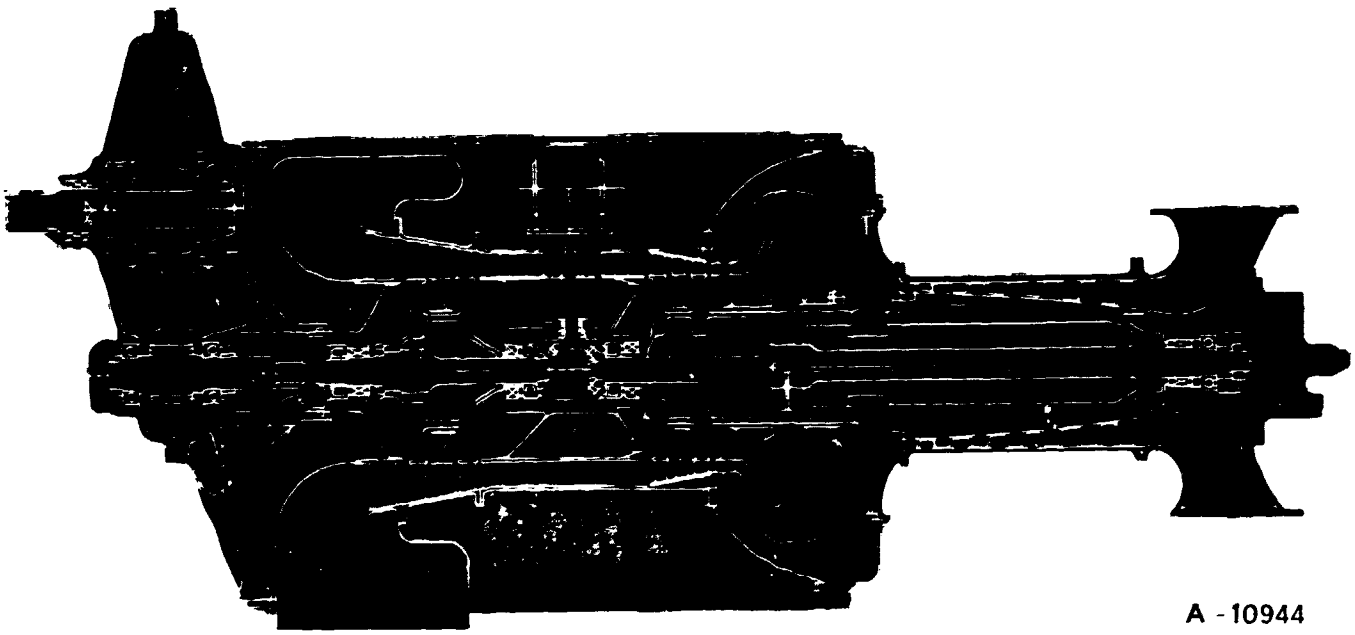

Figure 38. Turboshaft Engine

The engine was conceptualized for the case where the power turbine runs at close to gas generator speed. Further optimization could change this in favor of a lower speed power turbine to improve the gearing and overall power turbine design. Another version of the engine could use the shaft system from the T/F engine with a through-shaft gearbox at a modest increase in accessory cost and complexity of construction. Such a design would require a fuel management system similar to the T/F system described on the following pages. Obviously, this configuration would have the characteristic of greater commonality to the T/F at the expense of commonality to the T/P. As a free turbine, the engine would also be less responsive to transient inputs than the fixed shaft engine.

Manufacturing technology methods and processes are expected to be essentially the same as those described previously for the T/P engine construction.

TURBOFAN ENGINE DESCRIPTION

Figure 39 illustrates in cross section the selected concept for the T/F engine. The design utilizes a conventional two-spool shaft configuration with characteristics amenable to envisioned low-cost manufacturing technology, processes, and methods.

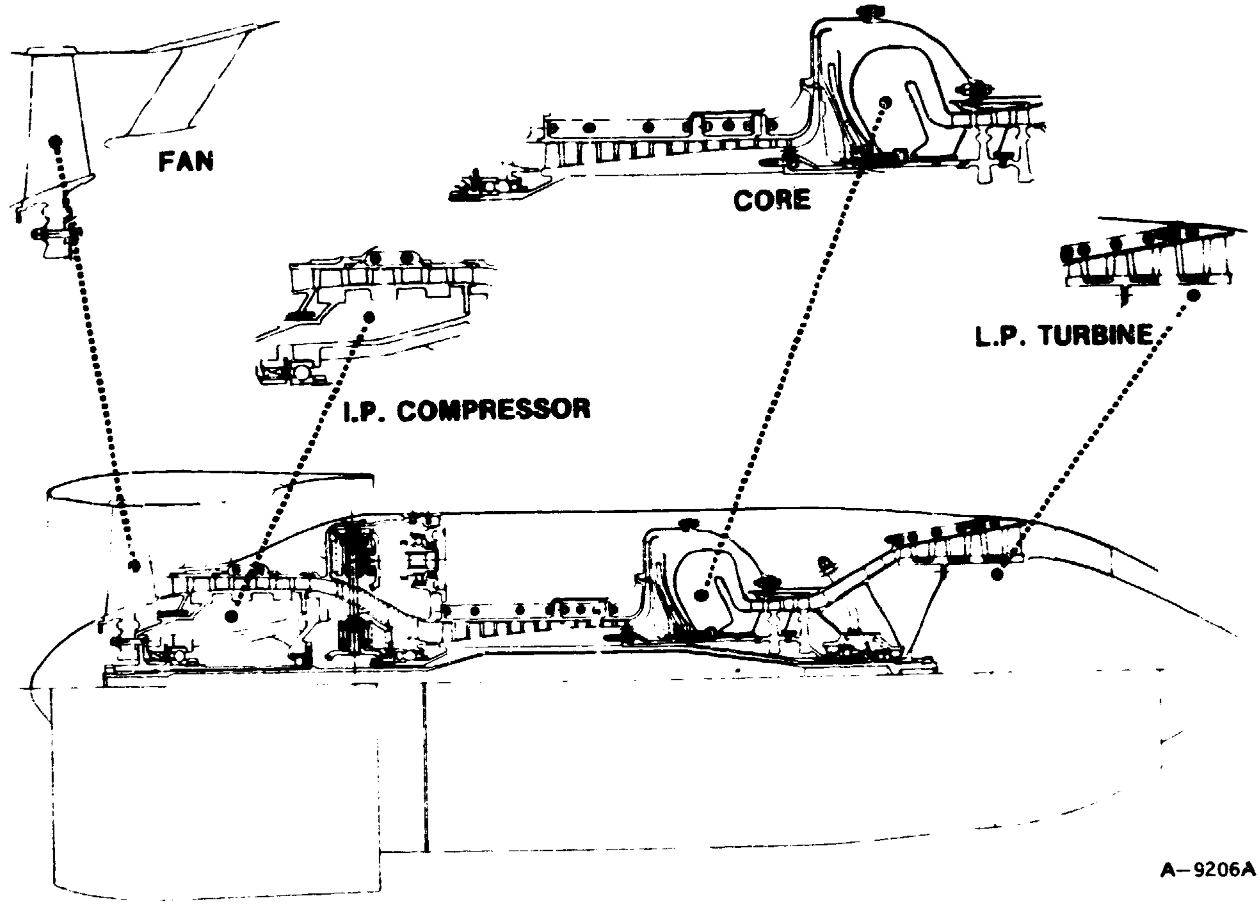

Figure 39. Turbofan Engine Components Concept

The nominal performance and basic design characteristics of the T/F are shown in Tables XLIV and XLV. The figures listed as nominal are those that could be reasonably expected without concentration on the development of a high-temperature turbine. The relative performance of an engine with improved components from an efficiency standpoint is also shown. This performance is believed achievable through a vigorous design and development program.

The design points for the T/F would be considerably different if a turbine of approximately 1478°K (2200°F) were developed and a higher bypass fan of approximately the same fan pressure ratio were substituted. Tables XLIV and XLV summarize the performance improvement that could be achieved with the higher temperature design point and with component efficiency improvements.

TABLE XLIV. LOW-COST TURBOFAN PERFORMANCE SUMMARY AT MAXIMUM RATING (UNINSTALLED)
(SI Units)

Component Efficiency Level	Nominal		Nominal		Improved		Improved	
Turbine Inlet Temperature Level	Nominal 1333°K		Improved 1478°K		Nominal 1333°K		Improved 1478°K	
Altitude, - m	0	9144	0	9144	0	9144	0	9144
Flight Mach No.	0	0.6	0	0.6	0	0.6	0	0.6
Ambient Temp., °K	288	229	288	229	288	229	288	229
Net Thrust, N	4342.8	1394.5	5586.5	1745.5	5196.0	1627.2	6919.7	2125.4
Engine Inlet Airflow, kg/s	18.07	9.08	25.58	13.28	20.18	9.93	29.81	15.07
BPR	5.32	4.80	8.97	8.02	5.32	4.89	8.98	7.99
HP Shaft Speed, rpm	35000	35785	36706	37725	34997	35553	36941	37736
TSFC, kg/N-h	0.0405	0.0693	0.0347	0.0633	0.0378	0.0653	0.0321	0.0592
Overall Comp. P_r	15.51	23.2	17.51	27.43	17.35	25.0	20.34	31.21

TABLE XLIV. LOW-COST TURBOFAN PERFORMANCE SUMMARY AT MAXIMUM RATING (UNINSTALLED) (English)

Component Efficiency Level	Nominal		Nominal		Improved		Improved	
Turbine Inlet Temperature Level	Nominal 1940°F		Improved 2200°F		Nominal 1940°F		Improved 2200°F	
Altitude, ft	0	30,000	0	30,000	0	30,000	0	30,000
Flight Mach No.	0	0.6	0	0.6	0	0.6	0	0.6
Ambient Temp, °F	59	-48	59	-48	59	-48	59	-48
Net Thrust, lbf	976.3	313.5	1255.9	392.4	1168.1	365.8	1555.6	477.8
Engine Inlet Airflow, lbm/sec	39.83	20.01	56.40	29.28	44.50	21.88	65.71	33.22
BPR	5.32	4.80	8.97	8.02	5.32	4.89	8.98	7.99
HP Shaft Speed, rpm	35,000	35,785	36,706	37,725	34,997	35,553	36,941	37,736
TSFC, lbm/lbf-hr	0.397	0.680	0.340	0.621	0.371	0.640	0.315	0.581
Overall Comp. P_r	15.51	23.2	17.51	27.43	17.35	25.0	20.34	31.21

TABLE XLV. LOW COST TURBOFAN PERFORMANCE COMPARISON - 9144 m (30,000 Ft)/ Mn 0.6/Standard Day

Component Efficiency	Nominal	Improved	Nominal	Improved
Turbine Inlet Temperature	Nominal 1333°K (1,940°F)	Nominal 1333°K (1,940°F)	Improved 1478°K (2,200°F)	Improved 1478°K (2,200°F)
Uninstalled				
BPR	4.80	4.89	8.0	8.0
OPR	23.2	25.0	27.4	31.2
Engine Inlet Airflow-kg/s (lbm/s)	9.08 (20.01)	9.93 (21.9)	13.29 (29.3)	15.06 (33.2)
Relative Fn	1.0	1.167	1.252	1.524
Relative TSFC	1.0	0.941	0.913	0.854
Installed				
BPR	4.89	4.97	8.3	8.23
OPR	22.3	24.1	25.8	29.6
Engine Inlet Airflow-kg/s (lbm/s)	8.98 (19.8)	9.84 (21.7)	13.06 (28.8)	14.88 (32.8)
Relative Fn	0.950	1.120	1.161	1.433
Relative TSFC	1.028	0.960	0.943	0.874

TURBOFAN COMPONENT DESCRIPTION

The T/F engine design employs a fan that operates to an approximate 305 m/s (1,000 ft/s) tip speed and a pressure ratio of 1.4 under standard conditions. The fan is attached to, and followed by, a three-stage intermediate pressure compressor producing about a 28°K (50°F) temperature rise per stage. This modest temperature rise enables the intermediate pressure compressor to be designed in accordance with the low-cost construction concepts intrinsic to the technology program. The IP compressor and fan are driven by a four-stage, low-speed turbine also based on low-cost construction concepts.

The high-pressure spool is basically derived from the common core elements described previously. Provision has been made for surge protection via a flow control device between the axial and centrifugal compressor components.

The engine accessories are arranged around the waist formed by the axial compressor rotor of the core. Major fuel control components and the starter/generator are common to the core design. Low-cost construction methods utilizing compromised aerodynamic shapes and low-speed components are used throughout the design.

SECTION 7

TECHNOLOGY PROGRAM PLAN

This Technology Program Plan presents an approach to a research, design, and development program to provide low-cost turbine power for general aviation in the next decade. The plan is intended to demonstrate an orderly and logical process culminating in the FAA type certification of turboprop (T/P), turboshaft (T/S), and turbofan (T/F) engines linked by a common core. The results of life cycle cost (LCC) studies presented herein indicate that turbine ownership in general aviation can produce significant economies over piston engine ownership and serve to reduce the depletion rate of world petroleum reserves. Engine design concepts based on a common core for economy are feasible and exhibit the potential for future growth in performance and fuel efficiency with advancing technology. The combination of these concepts with realistic program planning and systems engineering control offers promise that implementation will result in successful achievement of the stated objectives.

This plan is arranged in two-page displays presenting textual descriptions on each left-hand page and supporting graphics on each right-hand page. A summary of the total plan is provided on the following pages. The plan is sequenced to present development rationale and schedules (pages 136 through 151) followed by program cost projections (page 152). The scheduling is presented in two levels. The first level is a program overview supported by another level of detail for preliminary design, common core development, the development of each of the three engine types, and additional detail for core component and turbofan engine component development. The second level schedules were generated by iterating tasks against the major milestones until realistic and viable detailed plans resulted.

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PROGRAM PLAN SUMMARY

Design concepts for the GATE technology program (detailed in Section 6) are based on low-cost approaches for component construction and the development of a common core adaptable as the nucleus of the T/P, T/S, and T/F engines. Basic accessories (e.g. the starter/generator) will be compatible with all three engines. Low-cost construction techniques to be used require aerodynamic compromises in the designs based on blade configuration constraints, but benefit from low operating temperatures, modest temperature rises per stage, low pressures, and low rotational speeds at standard conditions.

The common core is composed of a six-stage axial compressor feeding a single-stage centrifugal compressor. The high-pressure compressor feeds a combustor of simple construction employing thermal barrier coatings and film-cooling techniques. Turbine rotors and the second stage nozzle are of medium, low-stress design with aerodynamic limitations due to high taper ratio, non-arbitrary twist, and compromised hub and tip incidence angles and blade span loading. In terms of part costs, common core components comprise 43.8 percent of the propeller and shaft engines and 30 percent of the fan engine. Common core development details are given on pages 140 and 141.

Planning for development of the common core and the propeller, shaft, and fan engines is displayed in a series of eight schedules with accompanying descriptions (pages 137 through 151). This display begins with a summary-level master schedule and progresses with coverage of the preliminary design program, common core development, and each of the engine development programs. Additional detail is provided for common core component and fan engine component development.

The master schedule provides an overview of the sequencing and logic for the 11-year term of the overall program. This level of planning illustrates a concentration on aerodynamic and thermodynamic analysis combined with extensive manufacturing technology investigations involving both the common core and engine development efforts. Also, considerable development test hours will be dedicated to refinement of fabricated hardware (3,000 hours on the common core, 17,000 hours on the propeller engine, 9,000 hours on the shaft engine, and 6,500 hours on the fan engine). The entire effort will be monitored and controlled by an in-depth systems engineering activity against the LCC discipline and performance requirements imposed on each engine type.

Preliminary design activity forms the basis for departure into the development activity. Preliminary design will build on the conceptual approaches presented in this plan and will result in initial designs which will circumscribe the performance requirements and development parameters for control of the development programs.

Common core development will be influenced by early design activity on each of the engines to allow the best mix of core components for optimum engine performance at low cost. However, once the common core component designs have been selected, the core will be a driving factor in all subsequent engine design and development work.

Each of the engines will undergo essentially the same kind of development procedure. Based on common-core and refined-component hardware, engine designs will go through a series of three release cycles. The first release will result in fabrication of hardware for development tests; the second will result in hardware for endurance tests leading to preliminary flight rating (PFRT) qualification; and the third release will provide hardware for endurance, environmental, and qualification tests leading to FAA certification. A technical manual activity is also included to provide operation and maintenance data for support of flight tests and certification.

A twenty-year, turbine-fleet cost benefit summary is shown on pages 103 and 108. This summary compares projected engine-related ownership costs for single- and twin-turboprop and twin-jet airplanes with comparable piston engine related costs. Note that a total savings of more than \$3.52 billion is possible through fleet turbinization. Data on page 152 shows that a GATE Technology Program investment of about \$0.11 billion (1,261.5 man-years of effort and \$48,619,000 material dollars) is required to enable the \$3.52 billion savings. More on the LCC benefit and GATE program cost subject is given in Section 5.

PROGRAM OVERVIEW

The Master Schedule displayed in Figure 40 portrays the logical and sequential development of the three types of turbine engines based on a common core design effort. This schedule provides a broad overview of how the GATE program stimulus can lead to successful delivery of certified engines which will meet the demands of general aviation in the late 1980's. Subsequent schedules in this plan will serve to illustrate the program planning in greater detail.

Major emphasis has been placed upon economy of operation and producibility. This goal can only be met by a carefully executed program of aerodynamic/thermodynamic analysis, manufacturing technology development, and exhaustive testing, with design iteration controlled by a pervasive systems engineering discipline. Development costs for this program will represent a substantial investment and the importance of a high level of planning and control cannot be overemphasized. Significant in this planning are 3,000 hours of development testing of the core design to establish a baseline for the three engine development efforts. Prior to completing this test activity, each of the three engine designs will have influenced the developing core design. However, once complete, the core design will be a driving influence on the engine designs.

Concurrent with core development, manufacturing technology investigations will be undertaken to establish optimum methods and materials for development of the propeller engine gearbox. The evolved gearbox design will be phased into the propeller engine design along with control and accessory designs, and the engine will undergo approximately 17,000 hours of development testing. Following PFRT, the development engine will undergo tests leading to FAA certification and delivery.

The shaft engine will undergo essentially the same development cycle as the propeller engine but with approximately 9,000 hours of development test activity. Much of the accessory development and test data derived from the propeller engine program will be available for refinement of both the shaft and fan engines.

The shaft engine fuel control is expected to be applicable to the fan engine because of the similar free turbine characteristics. Additional development of fan components will be undertaken to ensure optimum matching under operational conditions. Subsequent sections will deal with the details of development and matching of the fan, axial compressor, turbine, burner, and core.

The overall GATE technology program presented is based upon intensive investigations and the resulting concepts developed during the conceptual design phase. Activity during the study phase reported here has shown the design approaches presented and the goals of achieving economical production and operation to be feasible during the prescribed time period.

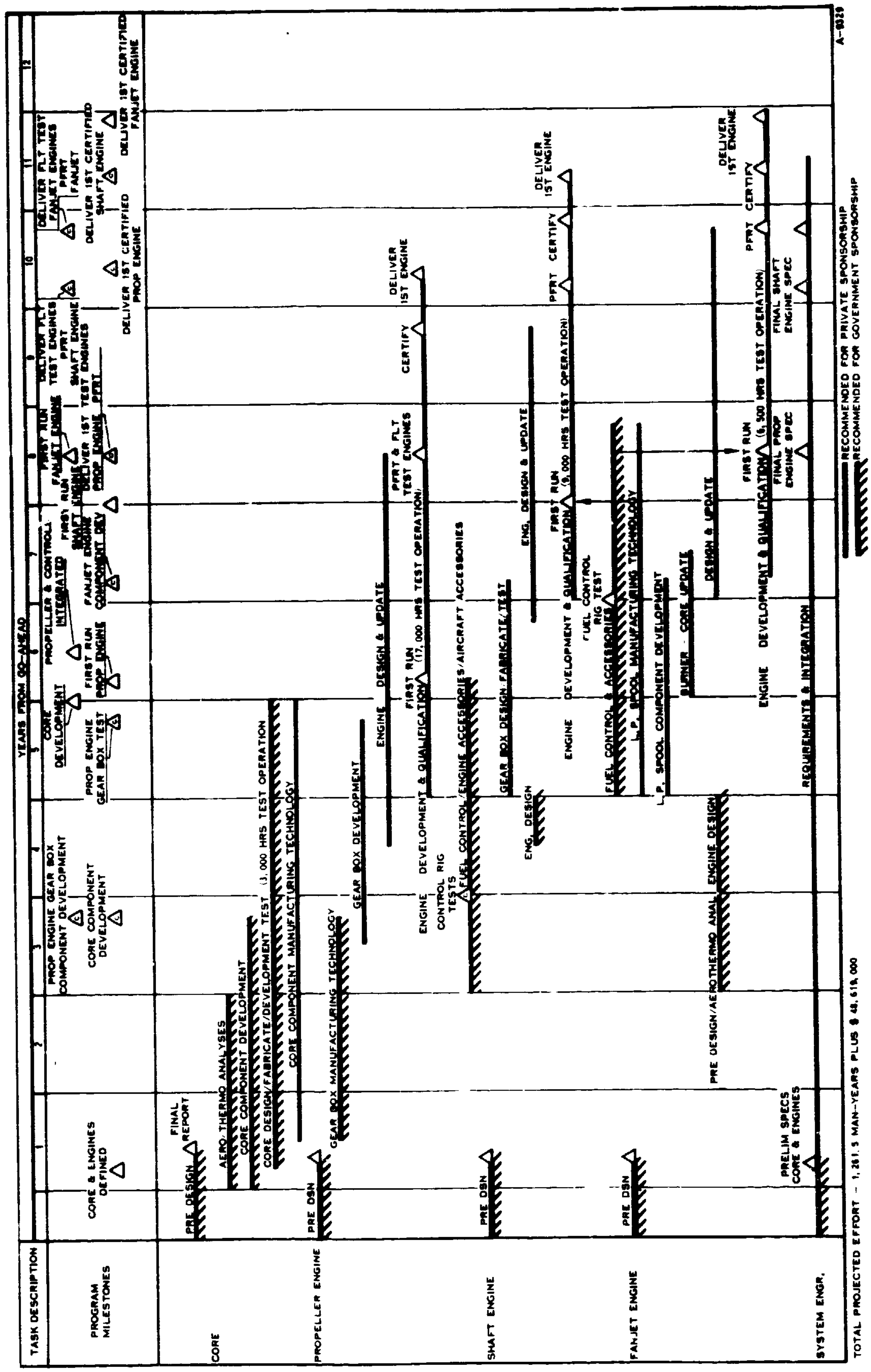

Figure 40. Program Overview

PRELIMINARY DESIGN TO REFINE CONCEPTS FOR TECHNOLOGICAL DEVELOPMENT

The technology program will begin with a 9-month effort to refine basic core and engine concepts into sufficient definition to allow commitment of development effort. This preliminary design activity will serve to focus subsequent design and development efforts so that the program can be controlled and directed toward a unified goal. This activity will result in a preliminary design report in the tenth month which will serve as the initial analytical baseline for the program. There will be no intent to limit design flexibility or to ignore technological breakthroughs or significant advances in the industry state of the art. When these occur, they will be investigated and utilized when appropriate. Planned iterations in every phase of the program will accommodate these actions.

Preliminary design will begin with cycle analyses and design optimization studies of the three engines. Performance sensitivity analyses will be made and aerodynamic flow paths described. Design layouts will be initiated for the core, the three engines, and the engine controls and accessories. These will be subjected to mechanical, maintenance, and safety analyses. Critical components will be defined and initial aerodynamic flow paths and performance data will be updated. Initial engine layouts will be used to drive the core design. As the core design evolves, it will be used to iterate the three engine designs toward final preliminary configurations. This data will be reviewed at the end of the sixth month and decisions made for update of the preliminary designs in each area.

Systems engineering will perform an independent audit of this activity throughout and will define requirements and develop specifications to integrate the analytical and design activities. LCC studies, maintenance and safety requirements, commonality considerations, and initial specification development will be used to impose design requirements.

Major emphasis will be placed upon core and core component design. The core design layout as described by the sixth month will undergo manufacturing technology investigations and core component aerodynamic/thermodynamic analyses continuing into the subsequent development phase. This activity, through the ninth month, will be reflected in the preliminary design report.

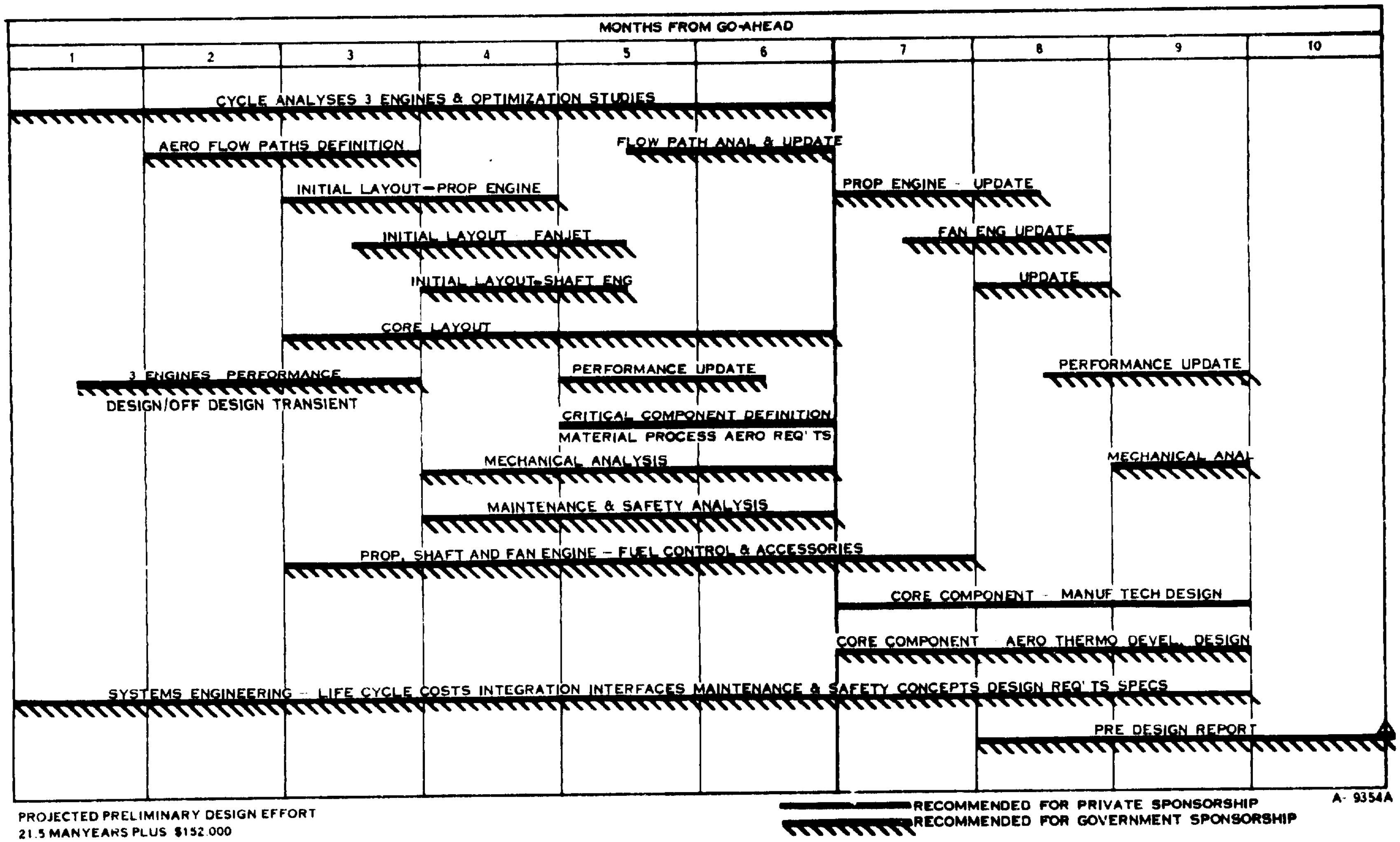

Figure 41. Core, Prop, Shaft, and Fan Engine Preliminary Design Schedule

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COMMON CORE DEVELOPMENT

The development of a common core for the three engines is driven by the objectives of low cost for each component. Durability and optimum performance for the hot sections of the design will be given prime consideration. As aerodynamics and thermodynamics are obviously constrained by the requirement for low-cost, careful matching of speed, temperature and pressure is indicated. These factors will be aided by intensive investigation and development of manufacturing technology and process/procedures refinement. As the design progresses, redesign and upgrading of core hardware will be accomplished based on test results.

Basic to development of low-cost designs are the evolution of an economical burner and approaches to bearing and suspension of the high-speed shaft. Materials, coatings, processes, shapes, and cooling concepts will undergo iterative investigation and development as shown by the schedule. The preliminary design baseline will lead into cooperative aerothermodynamic analysis, manufacturing technology development, and turbine/compressor/burner development. These will define the core design activity leading to approximately 3,000 hours of development testing. The compressors, burner, turbine, shafts, bearings, and accessories will be matched during this activity to form the nucleus for the subsequent engine development work. The tests planned for the core will be unpressurized but will yield data sufficient to harden the designs for use in the engine build-ups. Details of these activities are given on the following pages.

Systems engineering activity during this time period will include audit and control of the core program and continuing LCC study and refinement, airframe integration studies, propeller and control interface and design requirements, and the identification and update of propeller, shaft, and fan engine specification content.

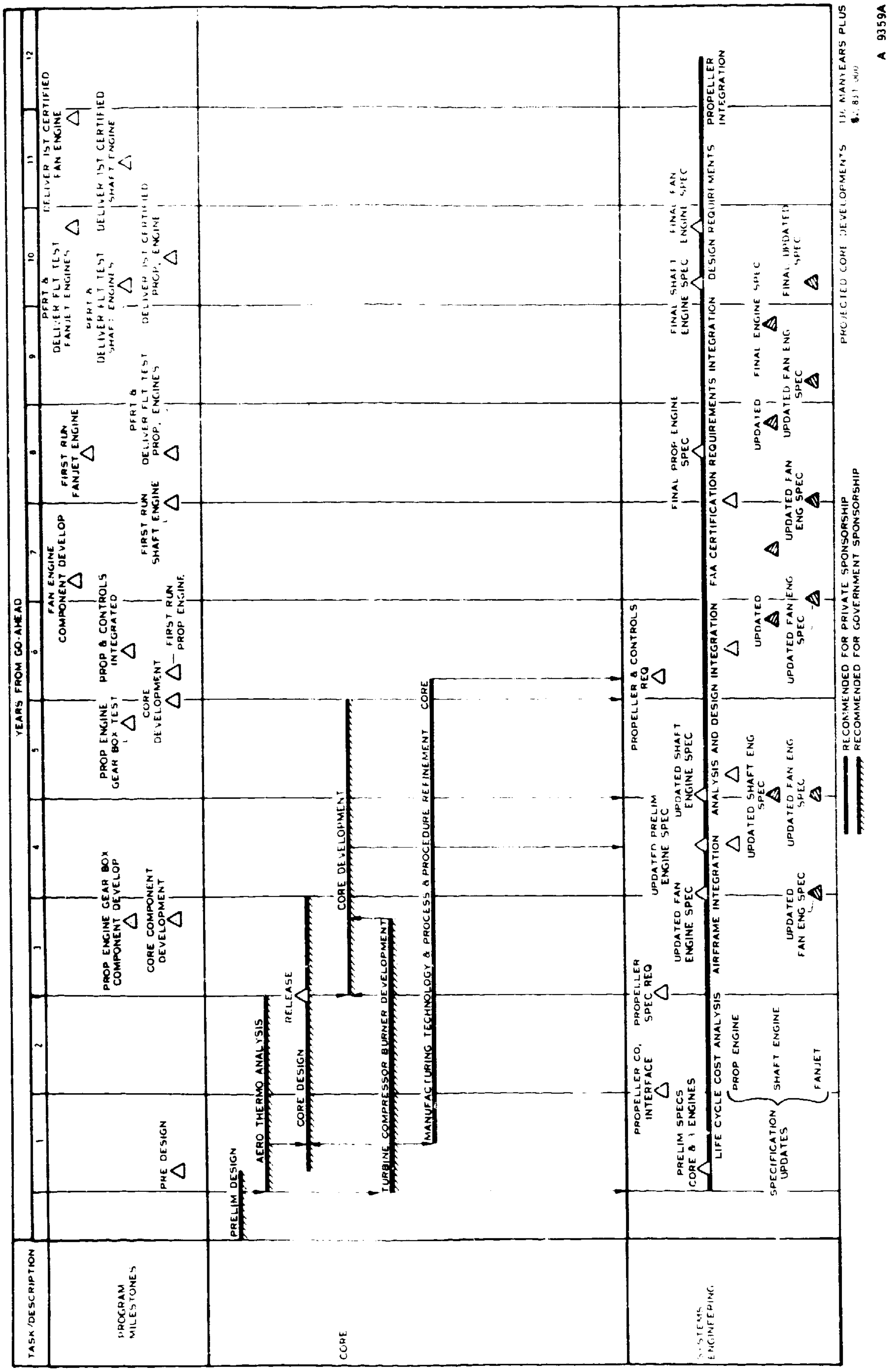

Figure 42. Common Core Development Schedule

CORE COMPONENT DEVELOPMENT

The axial compressor, centrifugal compressor, and turbine will undergo concurrent investigations for advanced manufacturing technology. Control design and the manufacturing technology approaches will continue as initiated during preliminary design. Tooling, methods, and process development will be undertaken as shown on the schedule. These activities will interact with alloy and material selection, and research of design properties, resulting in the development and buildup of prototype parts for integration into the common core for testing. Prior to release to the common core, each component will go through appropriate fabrication tests, nondestructive investigation, spin tests, and dimensional checks. The manufacturing processes will be refined and designs coordinated with engineering. Final-configuration fabricated parts will be available for propeller engine test at the end of the core test series.

Aerodynamic and thermodynamic testing to establish airflow patterns and heat and stress characteristics will take place in concert with manufacturing technology activity. One fabrication/test cycle is planned for the burner and two cycles are planned for the turbine and compressor. As these test-redesign-test activities are completed, results will be fed into the common core design and to the manufacturing technology activity, as required to maintain the best overall approach.

The common core design will progress based on inputs from the manufacturing and aerothermodynamic efforts. Fabrication and procurement of refined designs (including requisite controls and accessories) will be undertaken to assemble hardware for core tests. Hardware from these tests will be fed to the engine development efforts and design updates will be maintained. Aerothermodynamic analysis and manufacturing technology development will undergo concurrent refinement integrated by systems engineering control. The results of the two activities will be superimposed on the second design iteration for final proof parts fabrication and test.

A fully-integrated effort between design engineering, manufacturing technology, and aerothermodynamic analysis will be maintained by project engineering control throughout the process. LCC studies will continue to impose design and development constraints toward the prime objective of low-cost final hardware. Maintainability, reliability, durability, and safety data will be taken from all tests and will be considered in the evolving designs and controlling specifications. Systems engineering will update LCC and design requirements as required to maintain an integrated overall program.

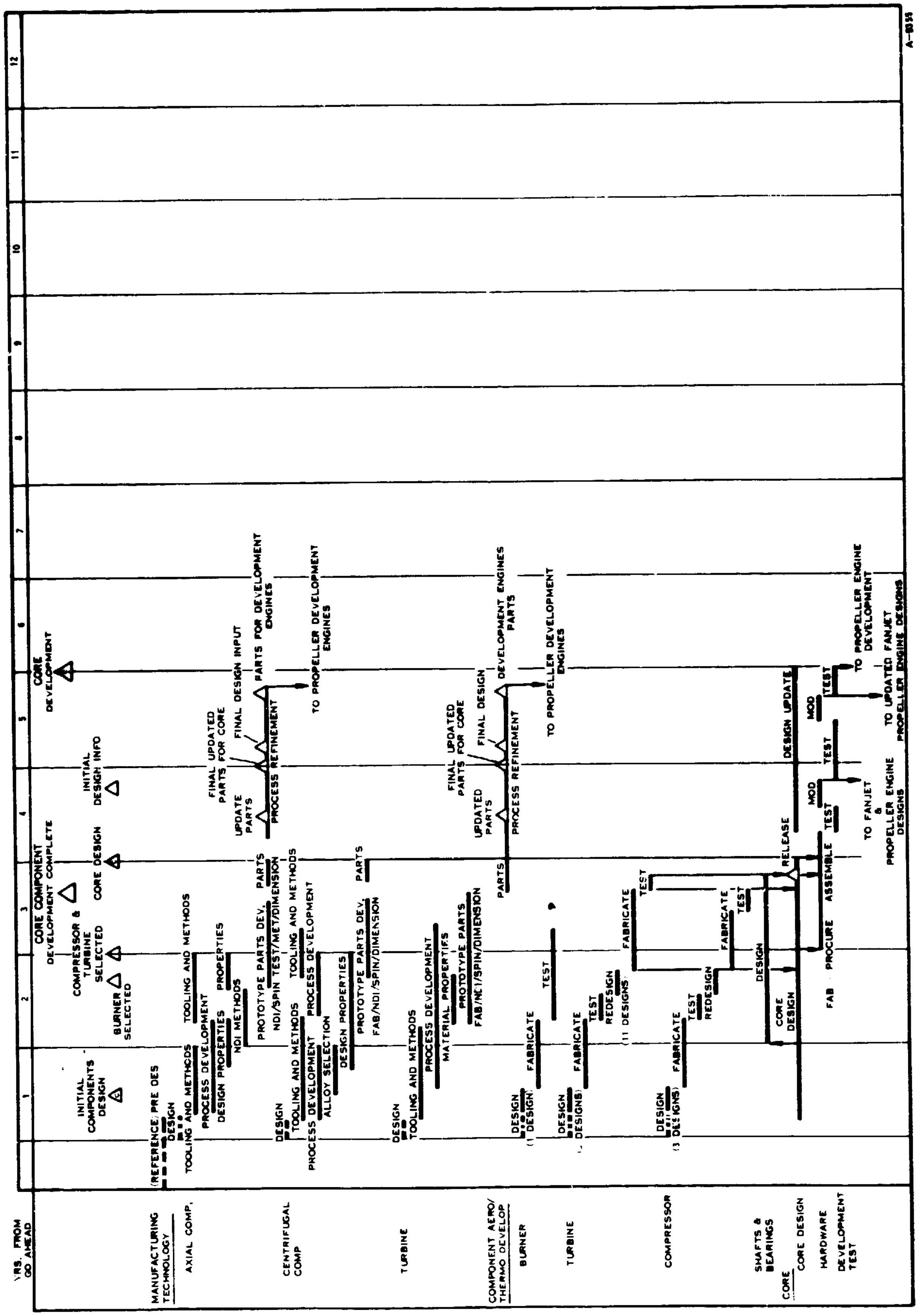

Figure 43. Core Component Development Schedule

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PROPELLER ENGINE DEVELOPMENT

Shortly after the start of common core development, manufacturing technology investigations into the propeller engine gearbox and components will commence. Also, based on common core work, the development of engine accessories, including a fuel control, can begin. These development activities will continue until a low-cost fuel control and other engine accessories are defined and the technology is released to permit the gearbox to be designed. The gearbox will be fabricated and undergo independent tests concurrent with engine buildup. Following engine accessory definition, aircraft accessory development will commence. The gearbox, controls, and accessories data along with inputs from the common core development effort will feed the initial engine design.

Final results from the gearbox qualification tests will be fed into the second design iteration for integration with engine development tests. These tests will continue and will provide data for design refinement. A next generation of gearbox, controls, and accessories will be fabricated for an endurance test leading to PFRT. Data from this testing will serve to further refine the engine design. Data from both the development test and the endurance test will be used to update the engine design including the gearbox design. A final design release of the complete engine will permit fabrication of hardware for the final endurance, environmental, and qualification tests leading to engine certification. A total of approximately 17,000 hours of development testing are planned.

During the final test phase, assembly procedures and test, operation, and maintenance data and analyses will be assembled into manuals for support of the engine. These manuals will be evaluated during PFRT. Data from flight tests following PFRT will also be used for manual update and design refinement during this period. Six months following certification, final manuals and the first certified engine will be delivered.

As in all other phases of this program, project engineering will coordinate the development activity, and systems engineering will control the integration. Propeller engine specifications will be updated and released to support each development milestone. The propeller interface will be released at the start of development activity. Propeller and propeller-control specifications will be issued and the final turboprop engine specification released at PFRT concurrent with initiation of final tests.

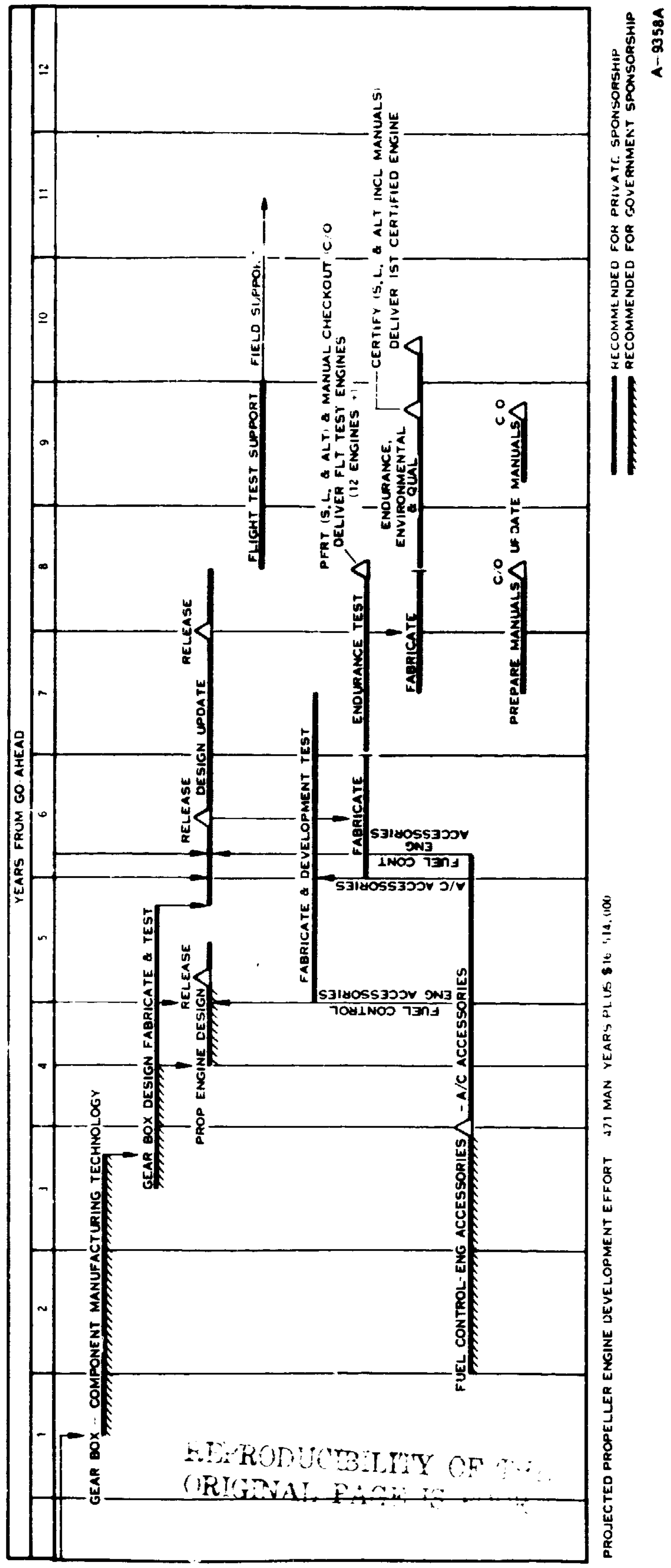

Figure 44. Propeller Engine Development Schedule

SHAFT ENGINE DEVELOPMENT

Design inputs from the common core development activity and the work on the propeller engine will initiate design of the shaft engine. The initial design activity (basically the preliminary design updated to accommodate changes in the common core and propeller engine requirements) will provide a baseline for gearbox and fuel control development. The common core used for the propeller engine will have a free turbine section added and require additional fuel control development. The fuel control development and bench test would apply to both shaft and fan engine concepts. Manufacturing technology and engineering analysis previously undertaken for the propeller engine will be applied to the design for the shaft engine. A gearbox design will be required to reduce free turbine speed to shaft drive speed. Once the gearbox and fuel control are ready for testing, engine design will resume based upon those configurations. The gearbox design, although differing from the propeller gearbox design, will employ much of the same manufacturing technology. Gearbox qualification testing will be oriented toward engine design-matching and compatibility with subsequent engine development test hardware. Test data will be injected into the design process, and fabrication of a shaft engine will be started for development testing. Data from this testing and from the continuing fuel control rig tests will be fed into the design update activity, leading to release of engine drawings for parts fabrication and subsequent engine endurance tests for PFRT. A total of 9,000 hours of development tests are planned for the shaft engine.

Data from the PFRT endurance test will affect the final design release for fabrication of hardware for endurance, environmental, and qualification testing. This testing will lead to certification. The first issue of shaft engine manuals will be available at PFRT for support of flight tests. These manuals will be updated based on results of flight tests and will be validated during the tests leading to FAA certification. Production-released drawings, specifications, and manuals will be available concurrent with delivery of the first certified engine.

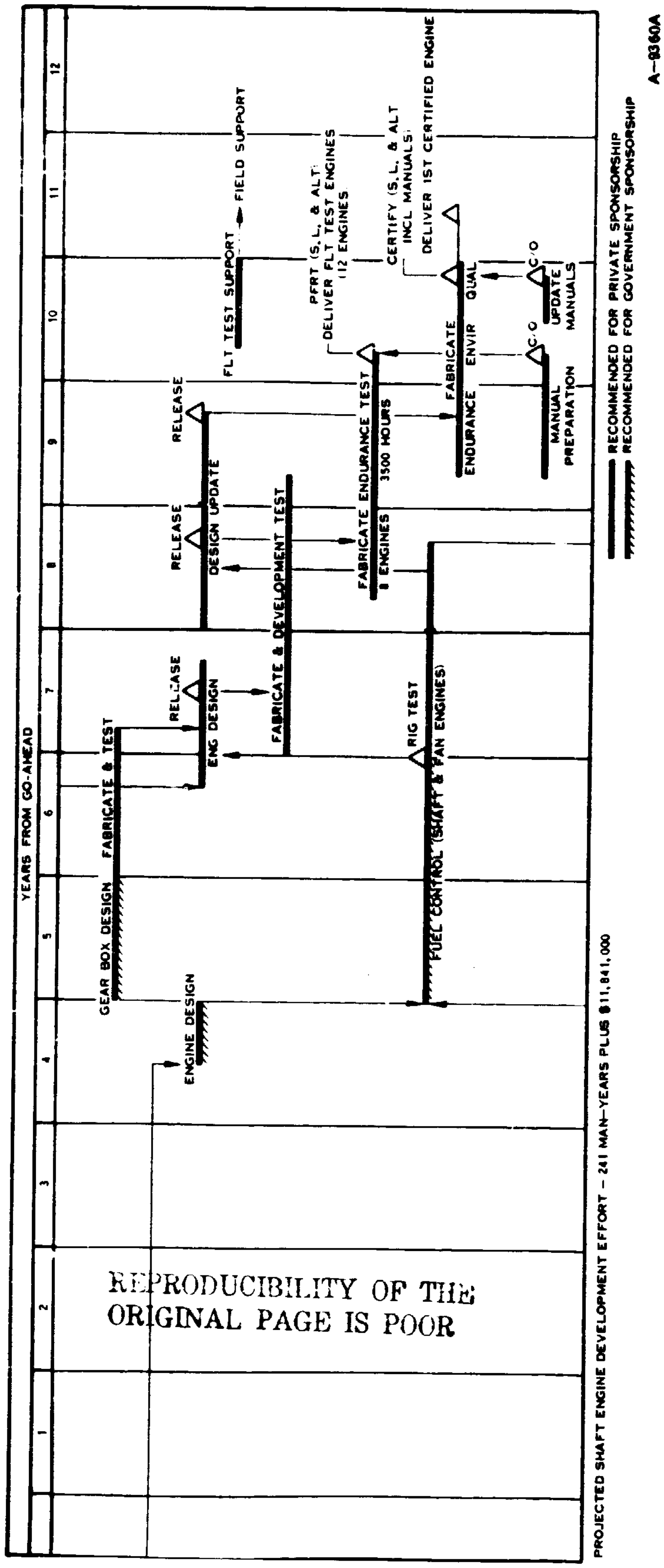

Figure 45. Shaft Engine Development Schedule

FAN ENGINE DEVELOPMENT

Preliminary design work and aerothermodynamic analysis, combined with results of the common core development activity, will define the baseline for start of the fan engine design. The culmination of this initial design work will coincide with the start of the fuel control development and rig test which were previously described as applicable to both the shaft and fan engines. Also beginning concurrently will be manufacturing technology investigations for the low-pressure spool design and a parallel effort to develop the spool. Component development efforts are detailed on the following pages.

Burner improvements and core updating will also be undertaken before resumption of engine design activity leading to fabrication release for the first engine development test. The fuel control rig test results and the manufacturing technology work on the low-pressure spool will be fed into another design iteration which will also benefit from development test data. This design will be released for fabrication of hardware for the endurance test leading to PFRT. PFRT hardware will be delivered for flight test. Approximately 6,500 hours of development tests are planned.

Design activity will continue with final test data from the development test and interim data from the endurance test used to define hardware for the endurance, environmental, and qualification test series leading to engine certification. As in the previous two engine development programs, engineering data and manuals will be available for support and delivery with the first certified engine.

The technology program displayed on the preceding series of schedules shows an orderly process for the design, development, test, and delivery of high-performance, low-cost engines meeting the requirements of general aviation. The iterative development process described, based on a common core design with maximum control and accessory similarity, enhances the probability of meeting the goals of the program.

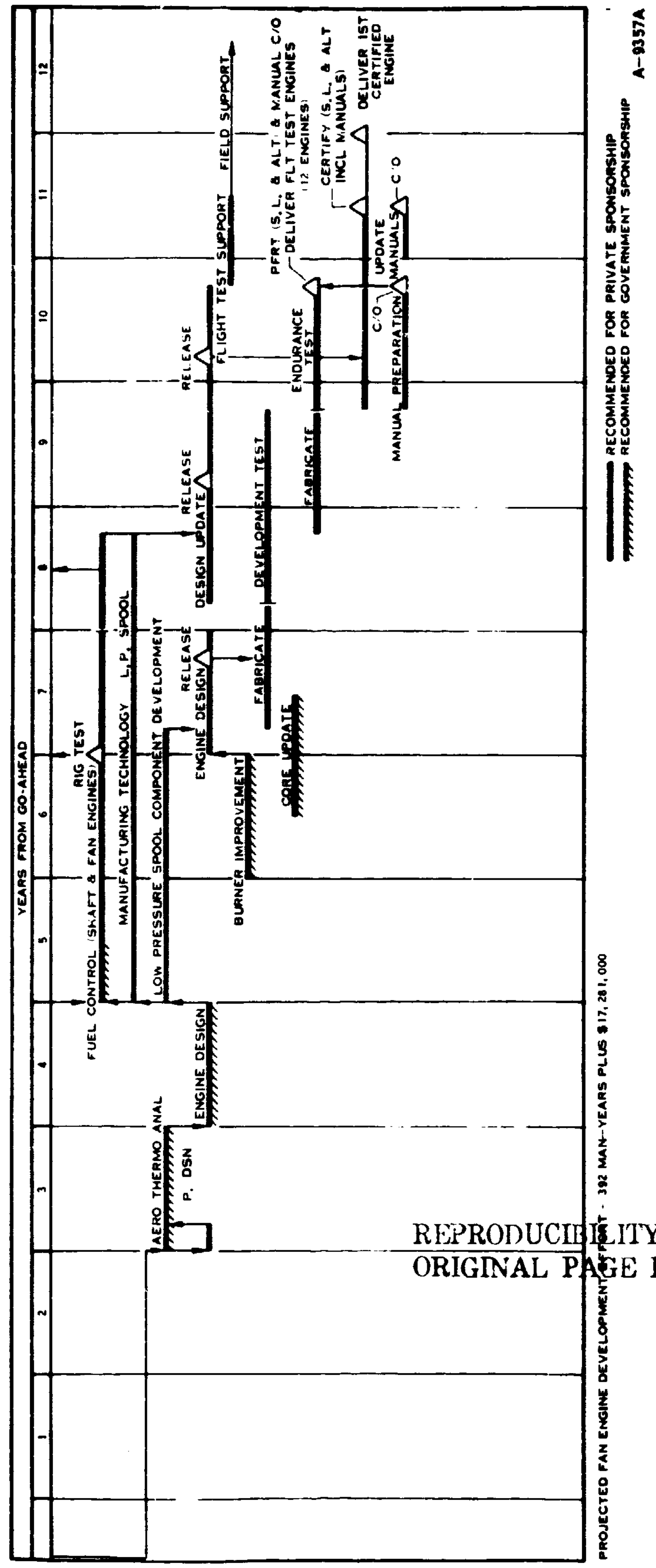

Figure 46. Fan Engine Development Schedule

FAN ENGINE COMPONENT DEVELOPMENT

The development of fan engine components is based on core development, manufacturing technology, and aerothermodynamic investigations. This additional level of detail indicates the emphasis that will be placed on the design and matching of the components for efficient fan engine performance. Also shown is the sequence and logic of the development superimposed on the engine development cycle.

Beginning with the completion of the initial fan engine design phase, component design will commence on the fan and turbine. Layout and design of the fan will be aided by flow path analysis activities, blade design, stress and dynamic analysis, and performance analysis. This design will result in hardware fabrication and testing for two cycles. The fan design will then be updated and the hardware will be subjected to testing on a spin/shake rig. Completion of this activity is coordinated with the required fan introduction into the engine design effort.

Initial turbine design will supply configurations for tooling, process, and methods development. Three base designs will be fabricated and subjected to test. This test activity will result in the selection of one optimum design which will be updated based on manufacturing development work, fabricated, and tested again. Data from this test will be fed to engine design and to process refinement activity for the development of engine parts for engine fabrication and testing. Update of the turbine design will continue as engine test data is received.

The axial compressor and burner will be subjected to design investigation to allow fabrication and one test cycle each. Data from these component tests will be reflected in updated designs to allow engine buildup and testing. Data from the common core development activity will be used to update axial compressor process development.

Core design matching for the fanjet engine will also be undertaken and the updated core fabricated and tested. Modifications from the common core are required because of the close aerodynamic coupling of the high- and low-pressure spool sections. The modified core, along with the other developed components, will result in the buildup and testing of a carefully matched, balanced, and efficient fan engine.

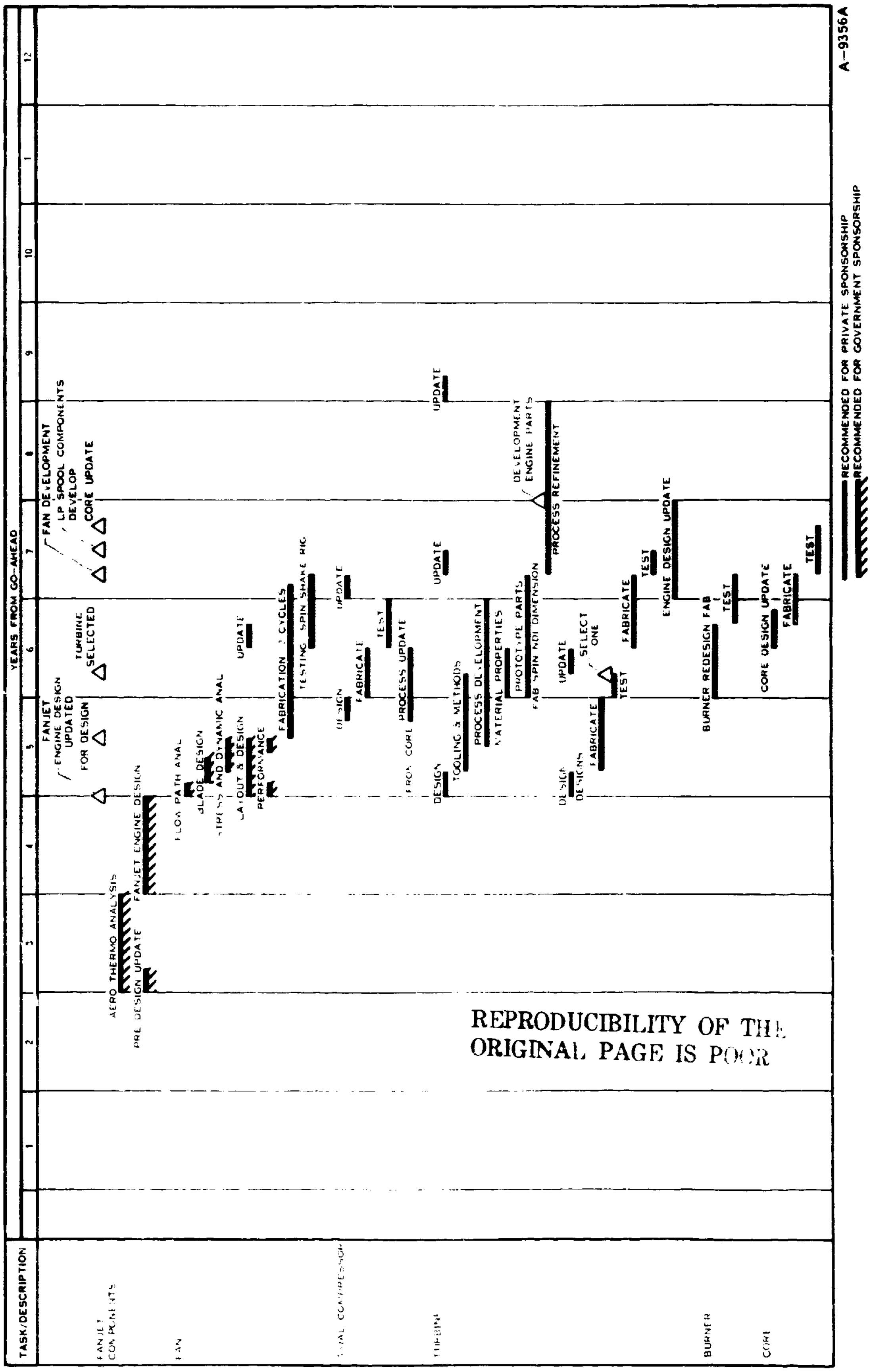

Figure 47. Fan Engine Component Development Schedule

PROJECTED PROGRAM COSTS

The Technology Program Plan described herein is estimated at 1,261.5 manyears and $48,619,000 material dollars (1978 economics). These projections are based upon experience with similar development activities. Cost estimates were collected (based on the specific activities presented in this program plan) from the functional work groups that will be required to participate. These data were reviewed and revised by management to present the most realistic budgetary and planning information possible.

Costs and material dollars as shown in Figure 48 are distributed according to basic hardware elements. It is felt that this illustration provides the best indication of projected requirements at this time. However, it in no way depicts a work breakdown structure, cost accounting scheme, or any other method that may be required for cost collection and control. The illustration is provided solely for future planning purposes.

The manyear data displayed is based on inputs from Design, Systems Engineering, Aerothermodynamic Analysis, Test Operations, Fabrication and Assembly, Logistics, Design Assurance, and support organizations. Material dollars represent direct costs for hardware and services projected as required for the program.

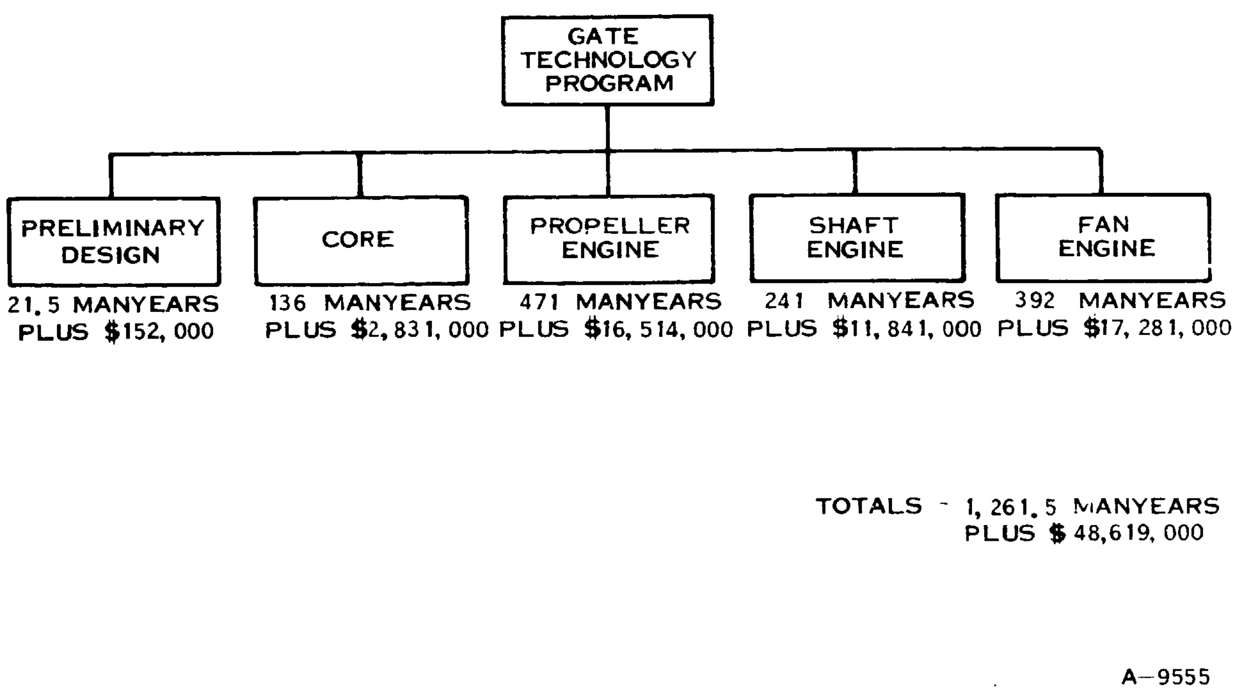

Figure 48. Projected GATE Program Cost Estimates

SECTION 8

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions resulted from the Market Analysis, Trade Study, and Common Core Evaluation:

1. A modest growth in annual aircraft unit sales is predicted for the decade ahead. This will be accompanied by a steadily growing fleet, because fleet additions will exceed retirements by a factor of about five to one. Most new aircraft sold will be for business use.

2. Because of fleet growth and characteristic weather influences, there will be a crowding in the flyable airspace below 3810 m (12,500 ft) that will influence buyer preferences toward pressurized aircraft that can operate in a greater volume of airspace.

3. Along with the need for pressurization will be a requirement for higher climb rates to facilitate flight at the higher altitudes, and higher cruise speeds to minimize the influence of the strong, high-altitude headwinds normally encountered by westbound flights. Deice/anti-ice capability will also be required.

4. There will be a demand for down-sized, turbine-powered business airplanes due to the high cost of fuel. These new airplanes will have adequate, but minimum, seating capacity (four to six seats), and they will be designed to be easy to fly with minimum crew requirements.

5. Flat-rated T/P engines in the 134 to 261 kW (180 to 350 hp) range and T/F engines producing about 4448 N (1000 lbf) of thrust will play an important role if fuel efficiency can be improved and cost constraints eased. Bleed air and power extraction requirements will exert an important influence on engine design.

6. The largest market will be for T/P engines because they can be more easily adapted to FAA-certified, single- and multi-engine, new-production and previously-owned airplanes, airplanes that will be better suited for small airport operations than turbofan-powered craft. There will be many more pressurized and icing-certified candidate airplanes for conversion in 1988 than today.

7. Because of the substantially larger market for T/P engines, if core design compromises are necessary, the compromises should be to the advantage of the T/P to assure its acceptance.

8. By judicious core design, it is probably possible to provide enough flexibility in compressor geometry and shaft speed to enable a common core to be used as an optimum T/P engine component as well as a component for the high-pressure section of a T/F.

9. A fixed-shaft, constant-speed T/P is preferable to a variable-speed, free-turbine design because it can be produced at a lesser cost, is compatible with lower cost control systems, is better able to supply bleed air for cabin pressurization during letdowns from high altitude, and enhances airplane go-around capability from aborted landings.

10. A concentric-shaft, two-spool T/F engine with the high-pressure spool derived from common core elements is the least costly of the T/F designs considered. Its performance potential is excellent, and it is lighter in weight than the second-choice tandem-spool contender. Other contenders included two geared-fan, F107 derivatives.

11. A free-turbine T/S engine design that uses the common core as the gas generator and the T/P fuel control (with features added for free-turbine overspeed protection) was selected because of cost and commonality benefits.

12. An innovative approach to the design and manufacture of small turbine engines is required to meet cost goals. The approach should not involve plans to run the engine hotter and faster, but rather slower and cooler. The advantages from the resulting stress reduction should be exploited.

13. Cost savings are possible through the augmented use of powdered metallurgy and non-precision casting techniques, and as a result of the geometric constraint of rotating components. Low-cost, multiple-blade-row axial compressors can be manufactured, for example, if the blading has uniform twist and constant camber, chord, and cross section.

14. Research oriented toward improving the durability of engine components is required in areas involving conductive cooling with thermal barrier coatings, coatings for environmental protection, hot isostatic pressing, etc.

15. The cost of engine accessories (fuel control, starter generator and propeller control) must be reduced and the durability improved. Accessories alone can equal the cost of a piston engine.

16. The productivity of the turbine-powered conceptual airplanes investigated that had piston-powered counterparts was competitive in terms of seat-km/l (seat-nm/gal) when flown at high altitude with the counterpart piston airplane. The performance improvement due to turbine engine substitution was remarkable in each case.

17. Although the candidate turbine engines were more costly than the piston counterparts, engine and airplane LCC were competitive because of reduced airframe, propeller, and engine maintenance costs, and because of the price difference between Jet A fuel and 100-octane aviation gas.

18. Calculated OEM prices for the T/P, T/S, and T/F engines in 1978 dollars were \$19,515, \$26,163, and \$25,352, respectively, excluding product liability influences.

19. Turboprop, turboshaft, and turbofan development programs based on a common core would require a minimum total investment of $0.11 billion before each engine type could be FAA-certified. Subsequent engine procurement and use over a 20-year period should result in a user savings of more than $3.52 billion when compared to the continued use of current-technology piston engines. Substantial fuel savings [up to 4.9 billion liters (1.3 billion gallons)] could be realized through turbine engine component efficiency and temperature-tolerance improvements. The investment cost would be 46 percent higher than for the nominal engines, however.

20. Because of the substantial investment required and the considerable development risk, the small turbine engine will probably continue to elude the small airplane without Government technology support. These small airplanes are already twice as productive as the newest airliners from a seat-km/l (seat-nm/gal) standpoint, but need expanded operational capabilities for added utility, comfort and, especially, safety. The small turbine engine offers promise in all these categories.

RECOMMENDATIONS

Turbine engine manufacturers interested in the small general aviation engine market have ongoing technology programs to advance the state of the art. For the most part, these are at a low level of activity because of the risk/return situation and available funds. These programs must be accelerated to produce more immediate results. This study report has defined the proper content of a Government-sponsored program to accelerate this activity through a blend of analytical and experimental work. Now is the time to start the hardware-oriented research (which can provide greater returns) and Government support for this effort is strongly recommended.

APPENDIX A

KEY INFLUENCES ON A 1988 GENERAL AVIATION MARKET SCENARIO

The general aviation market is very sensitive to a number of factors that could cause any long-range forecast to deviate far from the mark. Consequently, the assumption has been made that market perturbations will be evolutionary, not revolutionary. In this respect, it is assumed that there will be no major global conflict, no breakdown of the U.S. monetary system, no depression, no energy depletion, etc. Rather, brushfire wars in distant lands, moderate inflation (about 7 percent), moderate unemployment (averaging about 5.2 percent), continued high interest rates for airplane financing (11.0 to 11.5 percent), and increasing aviation fuel costs (due to inflation, taxation and scarcity) can be expected. On the basis of the evolutionary perturbation assumption, a modest general aviation market growth is foreseen for the decade ahead.

The prediction of modest growth can mean many things to many people, and it would be well to put this term in perspective. The confusion comes with respect to the index used for growth measurement. Two popularly used indices are annual unit production and annual dollar sales. Other indices include fleet size, aircraft operations logged by FAA control towers, flight services logged by flight service stations, and total hours flown by general aviation airplanes. It is possible to have a growing fleet and operations at record levels while new airplane sales are declining drastically. This occurs because aircraft retirements, which will number about 2,000 in 1978, fall well short of the number of new aircraft being added to the fleet, even during a very poor sales year. A Frost and Sullivan estimate (ref 1) of net additions to the total active general aviation fleet in the United States is shown in Table XLVI.

TABLE XLVI. FROST AND SULLIVAN ESTIMATE OF AIRCRAFT ADDED TO ACTIVE US FLEET

	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983
Factory Shipped	14,166	14,270	15,016	16,186	17,754	19,187	20,324	21,489	22,785	24,134
Shipped to US Market	8,499	8,562	9,760	10,521	12,428	13,431	14,227	15,042	15,950	16,894
Shipped to Foreign Market	5,667	5,708	5,256	5,665	5,326	5,756	6,097	6,447	6,835	7,240
Retired	1,449	1,562	1,760	2,000	2,000	2,400	2,600	3,000	3,300	3,500
Net Added to Fleet	7,000	7,000	8,000	8,521	10,428	11,031	11,627	12,042	12,650	13,394
Total Active Fleet	152,950	159,950	167,950	176,471	186,899	198,330	209,957	221,999	234,649	248,043

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The prediction of modest growth for the decade ahead is made here with reference to new airplane and new engine unit sales for domestic and foreign markets by U.S. manufacturers. The pace of the growth will be governed by the energy situation, airport/airways development, the regulatory environment, economic regulations, new technology, and product liability considerations. The paragraphs that follow discuss each of these influences in relation to a 1988 scenario for general aviation powerplants including those for rotary wing aircraft.

ENERGY INFLUENCES

The 1973/74 fuel crisis and the attendant Emergency Petroleum Allocation Act had a decided influence on general aviation that set the stage of activity for years to come. The full effects of the crisis were not obvious because of cross influences and the limited duration of the immediate problem. Nevertheless, the seriousness of the situation and the potential consequences of a recurrence has caused general aviation industry leaders to focus on the fuel economy of their present and planned products. Table XLVII lists observations of the effects of the 1974 fuel shortage on aircraft operations and sales. Some of the actions initiated to conserve fuel are listed in Table XLVIII. Additional actions which will probably be implemented with the increasing preciousness of fuel are listed in Table XLIX.

AIRPORT/AIRWAYS DEVELOPMENT

During the late 1960's, airport/airways development fell far short of what was required for the safe and expeditious handling of air traffic. The result was a series of air traffic controller slowdowns (traffic was handled "by the book"), traffic backups, and long holds on the ground and in flight, with attendant fuel wastage. The effect on general aviation fixed-wing aircraft sales was devastating, with sales falling from more than 11,000 in 1966 to less than 5,000 in 1971. Wichita, indeed, became an economically depressed area, and corrective action was clearly called for.

To reverse the downward trend in sales, the general aviation industry, in concert with the air transport industry, recommended legislative action leading to the establishment of an Airport/Airways Trust Fund. Monies for the Fund would come from excise taxes on aircraft tires and tubes, aviation gasoline, airline tickets, international head taxes, waybills, aircraft registration fees, and aircraft weight taxes. Proceeds from the Trust Fund were to be used to provide for the expansion and improvement of the nation's airport/airways system.

After the successful enactment of Trust Fund legislation into public law in May 1970, the job of airport/airways system upgrading was begun. As progress was made and the productivity of the National Aviation System increased, aircraft sales improved until today a more than 18,000 unit sales year is predicted for 1979. In December 1978 the Trust Fund balance was nearly 4 billion dollars.*

*The Weekly of Business Aviation, 5 March 1979, page 79.

TABLE XLVII. IMPACT OF THE 1974 FUEL CRISIS AND EMERGENCY PETROLEUM ALLOCATION ACT ON GENERAL AVIATION

• Multi-engine piston airplane sales declined during the 1975 and 1976 fiscal years while single-engine piston airplane sales increased.
• Turbofan/turbojet airplane sales leveled in FY'75 and declined in FY'76, reversing the strong growth trend of prior years. T/P airplane sales turned downward during FY'75 and then resumed an upward trend. The decline in FY'75 was due to a slowdown in engine deliveries resulting from an engine supplier strike. There was no lessening of demand for turboprops.
• Because of the imposition of the national 88.5 km/h (55 mph) speed limit on highways and motorist fuel acquisition problems, aircraft sales remained strong despite the fuel crisis and a sagging economy.
• Aviation fuel was allocated to fixed base operators on the basis of prior year sales, thereby creating spotty shortages. Preferential treatment in fuel dispensation was given to regular customers and locally-based aircraft. Itinerant aircraft experienced fuel acquisition problems.
• Flights had to make more fuel stops to obtain adequate gallonage, thus wasting fuel during descents, holding, approach, landing, taxi, takeoff and climbout.
• Local flying continued at a high level as did itinerant operations within the round-trip capability of aircraft.
• Long-distance flying, where aircraft are the most fuel-efficient, was curtailed.
• Flights were made with inadequate fuel reserve, and safety was compromised.
• Airplanes had to be left at destination airports for several weeks until they could be refueled. This required passenger and crew shuffling by other modes of transportation, which resulted in a waste of fuel.
• Condensation of water in empty fuel tanks created potential in-flight engine stoppage problems.

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TABLE XLVIII. FUEL CONSERVATION ACTIONS INITIATED DURING 1974 FUEL CRISIS

• Aircraft manufacturers initiated airplane drag reduction programs.
• Business jet redesign activity was focused on the substitution of turbofans for turbojets.
• Flight profiles were optimized and more use was made of area navigation (RNAV) equipment for making direct flights.
• Air traffic control issued corner-cutting and time-saving clearances.
• Traffic flow control procedures and airport quota systems were implemented by FAA to improve the flow of air traffic into congested airports and reduce delays.
• Training and proficiency missions were conducted on deadhead or positioning flights. Flights were consolidated where possible. Unnecessary and nonproductive flights were curtailed.
• A fuel reservation plan was initiated whereby aircraft operators could telephone ahead to a stopover point and reserve fuel before leaving on a flight.
• Engine use for ground operations was curtailed through tows from hangar to ramp, use of fewer engines for taxi, hold-taking at the gate with engines off, and engine shutdowns during short stopovers.

Vexation in the aviation community has been caused by the accumulating Trust Fund surplus and executive attempts to divert large sums for other purposes (e.g., FAA operating expenses, urban mass transit, etc.). These attempts have been challenged successfully to date on the basis of not being in accordance with the intent of Congress in establishing the Trust Fund. Also, considerable system upgrading is still in order and needed to ensure continued safe and orderly handling of air traffic and minimization of fuel wastage. No other expenditures, including those for improved engine fuel efficiency, will make as significant an impact on the efficient use of aviation fuel as those for airport and air traffic control improvements. Airplanes simply cannot be parked at the "side-of-the-road" when there are airborne traffic jams, and considerable power and fuel are used to sustain flight while in a holding pattern.

TABLE XLIX. ADDITIONAL ACTIONS TO BE EXPECTED WITH THE INCREASING PRECIOUSNESS OF FUEL

• During the new design phase, trade-offs of airplane aerodynamic efficiency versus production cost will be weighted more heavily on the side of aerodynamic efficiency.
• All-weather capability will be emphasized in downsized, pressurized, turbine-powered aircraft. Small, high-performance T/P and T/F airplanes sized to the passenger load requirements of business will emerge on the market.
• General aviation airplane cruise speeds will continue to increase, facilitating terminal area traffic flow and yielding large-airplane fuel savings.
• Airplane flying ease will be emphasized so that the businessman can fly himself and his associates to business meetings in a minimum-size airplane. A highly automated, simple-to-use, efficient air traffic control system will play an important role.
• Area navigation equipment will proliferate and its use will become the norm. Airways use will decline.
• Pilot training curricula will evolve toward a greater use of simulators and away from in-flight activities. Procedural training including navigation, instrument flying techniques, and operations within the air traffic control system will be emphasized, with the simulator playing an increasingly important role. In-flight maneuvers having little training value, such as lazy eights and chandelles, will be deleted from the curricula.
• Instrument proficiency and currency will be maintained through increasing simulator use.
• Turbine fuel specifications will be relaxed to allow more fuel to be obtained from a barrel of oil. Due recognition of this eventuality will be reflected in new engine designs.

The general aviation market prediction for the late 1980's assumes the wise use of Trust Fund proceeds for the benefit of aviation through the timely implementation of a well-conceived National Aviation System Plan, a plan that is responsive to new technology developments with respect to general aviation airplanes, engines, and avionics.

THE REGULATORY ENVIRONMENT

As the airport/airways system was upgraded to increase productivity, a need surfaced for new and upgraded airborne equipment and for periodic equipment checks for accuracy and proper functioning. Prior to the upgrading, aircraft operators voluntarily purchased new equipment in accordance with their financial abilities to do so and in order to take advantage of the added capability provided. To accelerate the upgrading, however, new equipment was mandated and unequipped aircraft were restricted from specified airspace. Examples of mandated

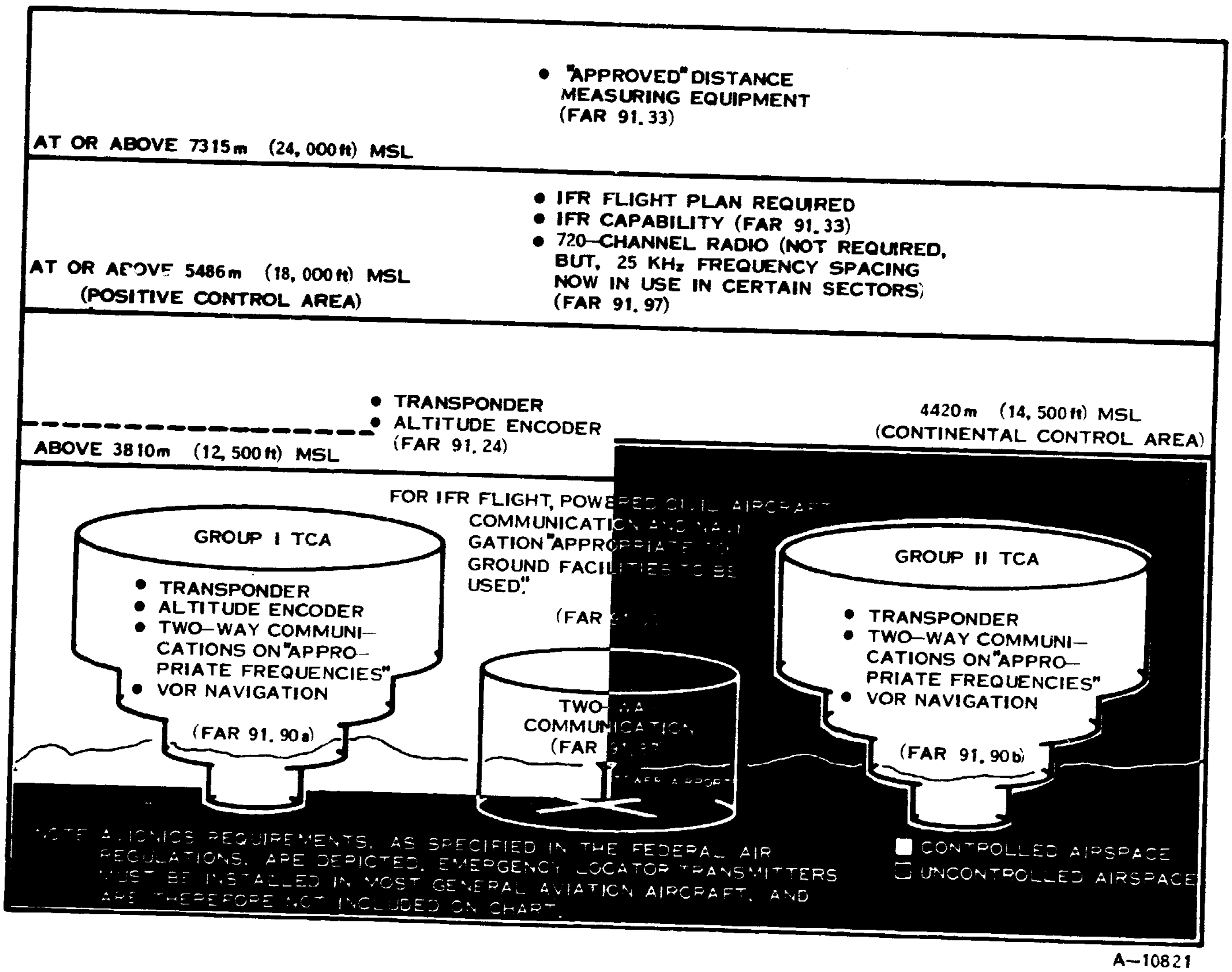

Figure 49. Avionics Required for Admittance to Different Types of Airspace

equipment include the two-way radio and successive requirements for more transmitting channels (today's transceivers have 720 channels), emergency locator beacons, anti-collision lights, VOR receivers, DME, transponders, encoding altimeters, and much more. Future equipment requirements could involve discrete address beacon systems, collision avoidance equipment, microwave landing aids, and navigational receivers with double the number of receiving channels. Figure 49 depicts some of the avionics required for admittance to specific airspace.

The financial burden of airplane ownership due to the cost of insurance, hangar rental, unscheduled maintenance, avionics repair, and fuel has been staggering for many years. Add to this the cost of current enroute and approach charts, and mandated annual inspections, airworthiness directive compliance, pilot physicals, biennial flight reviews, use fees, weight taxes, state registration fees, avionics upgrading, altimeter recalibrations, airspeed system leak checks, transponder checks, and locator beacon servicing, and the situation becomes very discouraging.

Because of an apparently unending chain of burden increases, many airplane owners have elected to sell their airplanes and seek less costly leisure-time pursuits. Leisure-time flying has thus been effectively throttled and aviation growth limited to manageable proportions through regulatory actions of the federal government and, to a lesser extent, state and local governments. (The major state and local government influence has been with respect to sales and property taxes.)

Regulatory actions, besides adding to the cost of airplane ownership, have caused the prices of new airplanes to skyrocket. The attendant insurance and interest costs have caused a substantial increase in airplane rental charges, with a corresponding increase in the cost of learning to fly and decrease in the number of student pilot certificates issued (down from about 160,000 in 1967 to 129,280 in 1976). To counter this decline, the General Aviation Manufacturers Association instituted a promotional program called TAKEOFF in September 1976 which is aimed at increasing student starts, successful completions, and, over the longer term, aircraft sales.

Many newly implemented regulations were instituted to improve safety and the productivity of the limited volume of airspace. Growth would have been ill-advised without the regulations, and it is being restrained because of them. Only technology is working to reduce the cost-inflating influence of an increasingly complex regulatory environment. In this respect, the greatest contributions over the last decade have been in the avionics/electronics realm. Here advances have improved aircraft productivity, providing an offsetting influence to rising ownership costs. The potential for similar productivity gains due to advances in powerplant technology is good.

A new type of regulatory influence is emerging that has the potential for grossly altering the delicate balance between regulation and growth. This influence creates economic burdens without providing corresponding returns with respect to safety, comfort or productivity. The EPA general aviation emissions standard promulgated in 1973 for implementation in 1979 is one such example.

This standard offered nothing to airport/airways productivity, nothing to airplane productivity, nothing to safety improvement (perhaps to safety degradation), and nothing to ride enhancement. Furthermore, it showed little likelihood of measurably improving air quality.

The recent EPA proposal to drop 1979 general aviation emissions standards "because the cost of implementation simply outweighs expected benefits," if adopted, will mean the resolution of a serious problem that has been facing the industry. Little opposition to the new proposal is expected.

An increase in the number of general aviation airports and the increased productivity of existing ones will go a long way toward staving off emissions problems. This will happen through expedited traffic movements and the reduction of hold times for takeoff clearance. The Airport/Airways Trust Fund plays an important role in this regard. Also, efforts to improve engine fuel economy will exert sufficient pressure to keep general aviation engine emissions at a low level.

Possibly an equally serious type of regulatory action as that dealing with emissions is the attempt to reduce the noise signature of business jets. Few in the industry will dispute the fact that jet noise reduction action is needed. This is evident from dockets of litigations over airport noise matters around the country and from community resistance to proposals for local airport expansion, a resistance that penalizes all of general aviation. The question is, how much noise reduction should be mandated.

Figure 50 summarizes present and proposed jet takeoff, approach, and sideline noise maximums and compares the performance of contemporary business jets with the standards. Note that only the Canadair Challenger with its Avco Lycoming ALF 502D turbofans meets proposed 1980 requirements. No business jet meets the 1985 requirements. The Cessna Citation, one of the quietest airplanes in its weight class, does not even meet the 80 FAR 36 requirements.

Figure 51 depicts proposed acoustical requirements in meaningful terms for T/F engines sized to the GATE interest. Because the 85 FAR 36 noise maximums do not vary up to the 4,536 kg (10,000 lbm) maximum aircraft weight limit, turbofans incorporating components designed for low noise generation producing less than 6672 N (1,500 lbf) of thrust can conceivably be made to meet the proposed requirements when installed in a proper nacelle. There is little data base in this regard, however, and tests of existing small T/F prototypes are clearly in order to establish the reasonableness of 85 FAR 36.

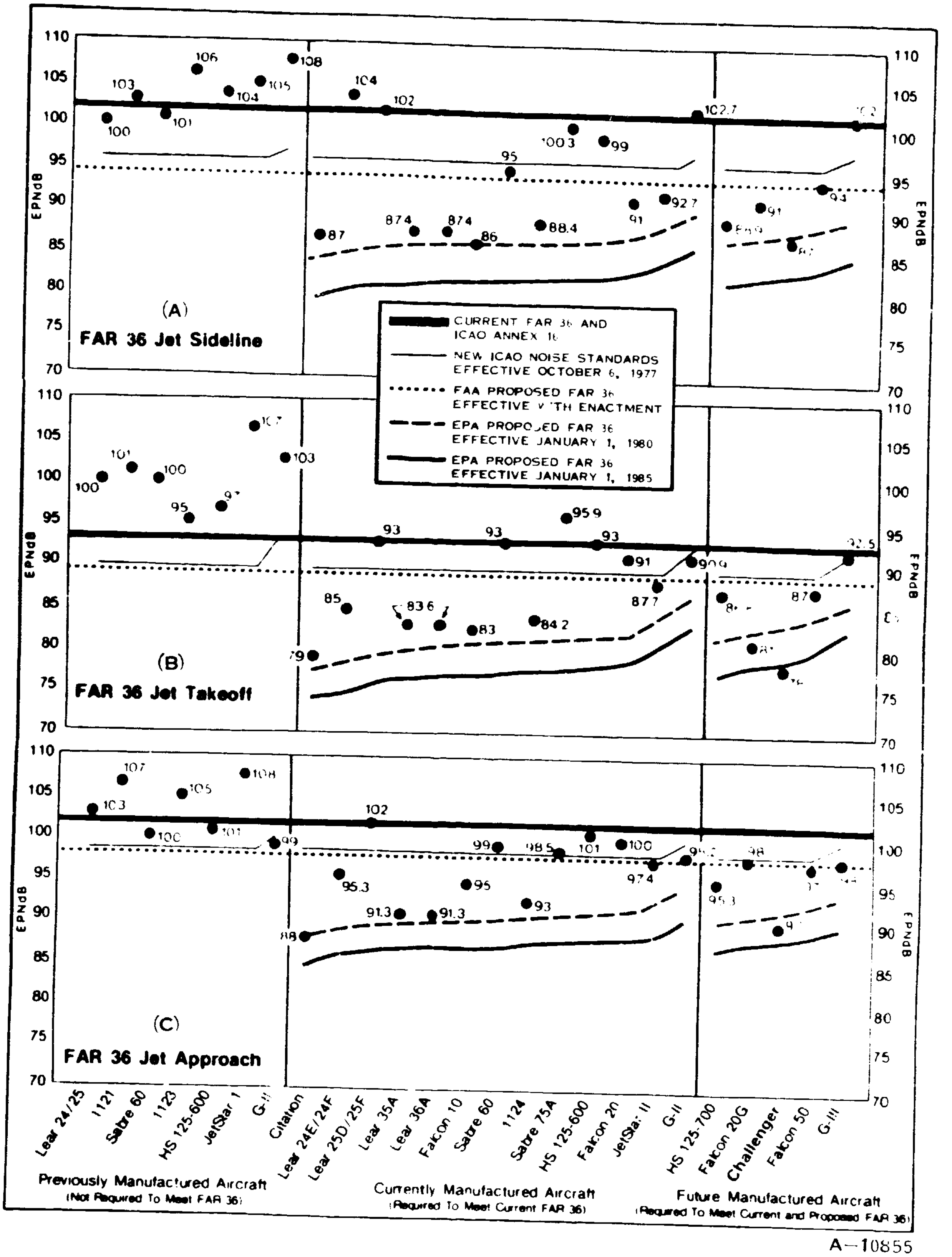

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Figure 50. Present and Proposed Business Jet Noise Maximums

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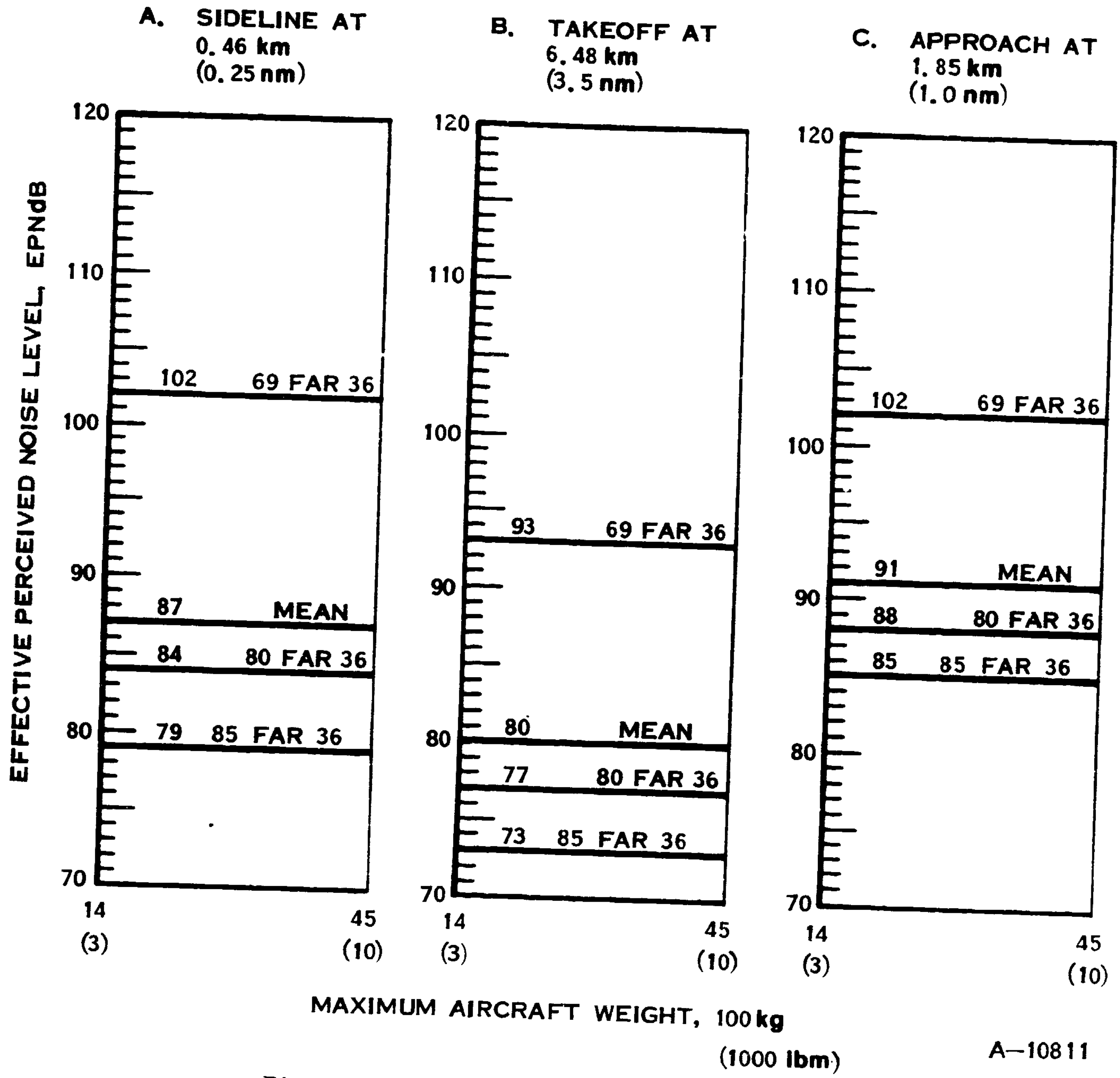

Figure 51. Proposed Compliance Noise Levels

Because the economic reasonableness and technical practicality of 85 FAR 36 have not been adequately assessed to date, 85 FAR 36 has not been assumed effective for a 1988 scenario. The proposed 80 FAR 36 regulations are expected to be adopted by the ICAO and should be in effect prior to and during 1988, however. With proper land use planning and appropriate zoning, the noise abatement afforded by 80 FAR 36 should be adequate. Table L lists the noise maximums under this regulation that are expected to apply to turbofan engines producing less than 6672 N (1,500 lbf) of thrust.

TABLE L. EXPECTED 1988 NOISE MAXIMUMS FOR NEWLY CERTIFICATED SMALL BUSINESS JETS (THRUST PER ENGINE ≦ 6672 N (1,500 lbf)

Measurement Point	EPNdB Limit
Sideline at 0.46 km (0.25 nm)	84
Takeoff at 6.48 km (3.5 nm)	77
Approach at 1.85 km (1.0 nm)	88

Noise regulations for propeller-driven small airplanes, and more specifically turboprop-powered small airplanes, for the 1988 timeframe are expected to correspond with those called out in FAR Amendment 36-4 (Appendix F, Part D, Paragraph F36.301). This amendment requires significant noise reductions affecting approximately 20 percent of the contemporary small aircraft types. It is expected to remain in effect throughout the 1980's. Table LI summarizes the regulation. Although FAR 36-4 is expected to have a negligible influence on 1988 market projections, it will influence conceptual engine designs for this market.

TABLE LI. EXPECTED 1988 NOISE REGULATIONS APPLICABLE TO NEWLY CERTIFICATED, TURBOPROP-POWERED GENERAL AVIATION AIRPLANES

Aircraft Weight	dB(A) Limit*
Up to 599 kg (1,320 lb)	68
599 kg < weight < 1497 kg (1,320 lb) (3,300 lb)	68 plus 1 dB/75 kg (165 lb)
1497 to 5670 kg (3,300 to 12,500 lb)	80

*As obtained from horizontal test flights at rated maximum continuous power 305 m (1,000 ft) over a single noise-measuring station with the airplane in cruise configuration.

The 1988 market scenario assumes that technology will stimulate the market and regulations will moderate the stimuli. Needed regulations will become law, and potentially destructive regulations will not survive.

ECONOMIC REGULATIONS

There are three types of economic regulations impacting the sales of general aviation aircraft. One type stimulates sales, another discourages them, and the third type stimulates business-use sales and discourages leisure-use sales. The type of regulations that stimulate the market include the following:

- Investment tax credit (currently 10 percent)
- U.S. government loan guarantee program for aircraft purchases (helpful for commuter airline purchases)
- Eximbank loan program (provides 30 to 55 percent direct credit) and loan guarantee program
- Business tax deductions for the use of private aircraft

Sales are defeated by punitive taxes that fatten general funds without benefiting general aviation. Several states levy this kind of tax in the form of specific ownership taxes, ad valorem sales taxes, fuel taxes, etc. Gellman Research Associates of Jenkintown, Pennsylvania is studying these under the sponsorship of FAA. Canada has had a very discouraging general aviation sales tax (12 percent) and excise tax (10 percent). In mid-November 1978 the controversial 10 percent excise tax on aircraft imports was dropped and the 12 percent federal sales tax was reduced to 9 percent.

The type of economic regulation that both encourages and discourages sales involves tax collections that benefit general aviation. These include the aircraft tire/tube excise tax, the 7-cents-per-gallon federal tax on non-commercial general aviation fuel, the $25.00 aircraft registration fee, the 2-cents-per-pound weight tax on piston-powered aircraft, and the 3.5-cents-per-pound weight tax on turbine-powered aircraft.

Foreign tariffs plus all of the aforementioned taxes have been assumed in the formulation of a 1988 market scenario. Additional user taxes have been excluded, because many that have been proposed would have a devastating effect on general aviation, if implemented. Examples of user taxes proposed by past and present administrations include:

- Administrative user charges for aircraft certification and pilot licensing. (On 21 September 1978 the House passed a bill which includes prohibitions against these user charges.)
- A $5.00 landing fee for landings at airports with FAA control towers.
- A $10.00 landing fee for landings at airports with FAA control towers equipped with radar.
- FAA financing of some of its operating costs with Trust Fund money.
- A 4-cents-per-gallon federal tax increase on aviation gas to 11 cents per gallon.

- Graduated federal fuel taxes peaking at 35 cents per gallon in 1980.

- A 20 percent excise tax on new general aviation (non-commercial) aircraft.

A DOT study released 14 January 1977 entitled "National Transportation Trends and Choices" forecasts reductions in general aviation activity by 1990 ranging from 4 to 41 percent depending on the activity parameter used. A major reduction would result from government attempts to fully recover costs for general aviation services. The industry response to the DOT study has been to demand more efficiency in government and the elimination of unwanted government services. The National Pilots Association, for example, has suggested the following steps:

- A review of FAA missions at its Atlantic City, Oklahoma City, and Cambridge, Massachusetts facilities, with an eye toward a geographic merger and the elimination of overlapping functions.

- A reevaluation of FAA pay scales.

- Personnel reductions.

- A possible transfer of air traffic control functions to a profit-oriented public utility-type company.

NEW TECHNOLOGY

Twenty years ago there was little general aviation instrument flying. This was because the then-existent air traffic control system and available avionics were primitive by today's standards. Pilot workload was high, requiring a level of proficiency possessed by few general aviation pilots. Deficiencies with respect to instrument flying, therefore, caused small airplane productivity to suffer.

Today, general aviation instrument flying is commonplace because of the availability and increased use of sophisticated avionics equipment. One has only to listen to one of the many air traffic control frequencies to convince himself of this fact. A 1976 FAA document (ref. 3) conservatively forecasts that the general aviation category of instrument operations will grow at an average annual rate of 7 percent through FY 1988.

To date, huge sums have been spent to computerize the world's air traffic control systems. In airborne electronics, however, there has been only a modest beginning toward capitalizing upon the potential that the digital computer holds for helping the pilot do his job. Microprocessors and microcomputers are now slowly easing their way into aircraft electronics. In the decade ahead, these tiny devices will make very significant changes in the avionics world.

As the "micros" proliferate, the time of the digital integrated avionics system and computerized flight management system will come. Signal multiplexing with the attendant combining of functions from separate black boxes is already commonplace. With further progress, a single digital computer could control turbine engine fuel flow, a stability augmentation system, an autopilot, a flight director, a collision avoidance device, and navigational system displays. To conserve precious panel space, some information could be displayed on the same cathode ray tube as weather information. Triple and quadruple redundancy could be provided to ensure system reliability. The relief in pilot workload thus provided would allow non-professional general aviation pilots to operate high-performance airplanes with greater precision and safety than is possible today. Small airplane utility would also improve to the point of being competitive with commercial airline experience, i.e., if the small airplane performance were to rival airliner performance.

While engines that may emerge as the result of a general aviation turbine engine activity will probably become available before digital integrated avionics and computerized flight management systems mature, they will see service in an era characterized by pushbutton piloting, coupled autopilots, navigational precision, and intermittent positive control conflict detection and alerting. There will be an accompanying demand for appropriately powered small airplanes that can take full advantage of the utility provided by the new airborne electronics, e.g., by being able to fly above the weather on a straight line course from a departure gate to an arrival gate for an approach at the destination. Enroute zigzagging for weather avoidance will be shunned. The preferred airplane will have sufficient power to provide an adequate climb rate, and adequate quantities of bleed air and electrical energy for anti-ice, deice, cabin pressurization, and cabin climate control. A quiet, vibration-free ride will be stressed.

The theme in the automotive world today is "smaller is better," and this will carry over into the aviation world. In the late 1980's, businessmen will no longer be whisked around the country in business jets which, in one coast-to-coast trip, consume as much fuel as it takes to heat a home for one year. Small engine technology will therefore be stressed so that smaller high-performance airplanes can be developed which will lessen the gap between available seats and the average passenger load. Table LII provides average passenger load data as obtained from a 1975 FAA-sponsored survey by Civil Air Patrol cadets.

TABLE LII. AVERAGE NUMBER OF PERSONS TRAVELING IN GENERAL AVIATION AIRCRAFT (1975 Survey)

Aircraft Type	Average Number Of Travelers (Including Crew)	Crew Requirements
Single-engine piston	2.1	1
Helicopters	2.9	1
Multi-engine piston	3.8	1
Turboprop	5.7	1
Turbojet/turbofan	5.4	2

Product Liability

In 1971 the general aviation industry was rudely awakened to the financial realities of product liability by a multi-million dollar jury award in connection with a 1968 light twin-engine airplane crash. Since that time, the major aircraft manufacturers have collectively paid out millions of dollars in settlements and judgments, and it is estimated that 2,000 product liability suits against light plane manufacturers are now in litigation. No one knows how many more claims are being settled out of court. Because of the large number of claims, defense costs, and settlement costs, product liability insurance rates have skyrocketed, with attendant product cost increases.

The industry-wide average product liability cost is about 7.5 percent of gross sales. About 5 percent goes directly to insurance premiums, with the rest attributable to time lost by employees responding to lawsuits and other costs. By 1980, premiums could reach 10 to 12 percent.

Some argue that safety may in fact suffer because of product liability litigation. The manufacturers are afraid to make improvements, goes the argument, because any safety improvement could be considered a tacit admission that the appliance was originally not as safe as it could have been. Also, manufacturers have been reluctant to commit themselves to promising new production techniques and processes and potentially superior new designs because of the fear of product liability suits. Airplane manufacturers, for example, have been slow to adopt bonded construction techniques because of apprehensions about bond strength 20 years hence. There is a similar reluctance to use composite airframes because of concerns over quality control inspection techniques, periodic airworthiness inspection techniques, and lightning protection.

A number of suits have involved powerplant and propeller structural failures. Fearing litigation, engine manufacturers have been slow to undertake new engine development programs, and prospering airframe manufacturers seldom encourage such programs by planning prototyping activities around experimental engines. Also, many of the smaller component manufacturers have gotten out of the general aviation business altogether because of liability vulnerability, and others have raised prices substantially. The FAA, which certifies engines and airplanes as safe for production, has tightened certification regulations to the point that added millions of dollars are required for engine and airplane type certification. The net result of all this has been that the grudging progress of light plane design has been brought almost to a standstill, while new airplane costs have escalated to the point of being beyond the reach of most individuals and many small businesses.

Prior to 1988, the legal pendulum governing strict liability in tort (wrongful act for which a civil action may be filed) is expected to swing in a direction more favorable to manufacturers. Some probable changes will involve:

- A requirement to prove negligence on the part of a manufacturer, not just a defect

- A reinstatement of contributory negligence as a defense against product liability suits
- Liability in accordance with the state of the art at the time of manufacture rather than at the time of the accident
- A disallowance of evidence that an airplane or engine was defective simply because later improvements were made

The sooner the legal pendulum swings the opposite way, the sooner the flight envelope of general aviation airplanes can be expanded through technology which is now latent. Progress in the face of tort law has slowed, but by the mid-1980's it will resume after corrective action has been taken.

APPENDIX B

ENGLISH-TO-SI UNIT CONVERSION TABLE

Parameter	English Unit	Multiple By	To Obtain SI Unit
Length	Inch (in)	2.54×10^{0}	Centimeter (cm)
	Feet (ft)	3.048×10^{-1}	Meter (m)
	U.S. Statute Mile (mi)	`.609344 x 10^{0}	Kilometer (km)
	Nautical Mile (nm)	1.85324×10^{0}	Kilometer (km)
Area	$(\text{Inch})^2$ $(\text{in})^2$	6.4516×10^{0}	Square Centimeter $(\text{cm})^2$
	$(\text{Feet})^2$ $(\text{ft})^2$	9.290304×10^{-2}	Square Meter $(\text{m})^2$
Volume	$(\text{Inch})^3$ $(\text{in})^3$	1.6387064×10^{1}	Cubic Centimeter $(\text{cm})^3$
	$(\text{Feet})^3$ $(\text{ft})^3$	$2.8316846592 \times 10^{-2}$	Cubic Meter $(\text{m})^3$
	Gallon (gal) (U.S. liquid)	$3.785411784 \times 10^{0}$	Liter (l)
Velocity	Feet/sec (ft/s)	3.048×10^{-1}	Meter/sec (m/s)
	Feet/min (ft/min)	3.048×10^{-1}	Meter/min (m/m)
	Statute mile/hour (mi/h)	1.609344×10^{0}	Kilometer/hr (km/h)
	Knot	1.85200×10^{0}	Kilometer/hr (km/h)
Force	Pound force (lbf)	4.44822161×10^{0}	Newton (N)
Mass	Pound mass (lbm)	4.5359237×10^{-1}	Kilogram (kg)
Pressure	Pound per square inch (lbf/in^2)	6.8947572×10^{0}	Kilopascal (kPa)

NOTE: One N/m^2 = 1 pascal
One atm = 101.325 kPa

Parameter	English Unit	Multiple By	To Obtain SI Unit
Stress	KSI	6.8947572×10^{0}	Megapascal (MPa)
Density	lbm/in^3	2.76799×10^{1}	Gram/Centimeter^3 (g/cm^3)
Flowrate	Pounds/hour (lbm/h)	4.5359237×10^{-1}	Kilogram/hr (kg/h)
Flow Parameter	$\frac{\text{lbm}}{\text{s}} \frac{\sqrt{^{\circ}\text{R}}}{\text{psia}}$	4.90355×10^{-2}	$\frac{\text{kg}}{\text{s}} \frac{\sqrt{^{\circ}\text{K}}}{\text{kPa}}$

Fuel Efficiency	Nautical mile/gallon (nm/gal)	4.892467×10^{-1}	Kilometer/liter (km/l)
Power	$\frac{\text{in-lbf}}{\text{s}}$	1.129848×10^{-1}	Watt (W)
	$\frac{\text{ft-lbf}}{\text{s}}$	1.3558179×10^{0}	Watt (W)
	Horsepower (hp)	7.4569987×10^{-1}	Kilowatt (kW)
Specific Output Power	$\frac{\text{hp . s}}{\text{lbm}}$	1.6439869×10^{0}	$\frac{\text{kW . s}}{\text{kg}}$
Specific Thrust	(lbf-s/lbm)	9.80665×10^{0}	N-s/kg
Specific Fuel Consumption (Thrust)	TSFC (lbm/lbf-h)	1.01972×10^{-1}	kg/N-h
Specific Fuel Consumption (Power)	BSFC (lbm/hp-h)	6.082774×10^{-1}	kg/kW-h
Temperature	Deg. Fahrenheit (^{o}F)	$T_k = \frac{5}{9} (T_F + 459.67)$	Kelvin (K)
	Deg. Rankine (^{o}R)	$T_k = \frac{5}{9} T_R$	Kelvin (K)

NOTE: $T_k = T_{celsius} + 273.15$

Energy	Btu	1.055056×10^{3}	Joule (J)
Enthalpy	(Btu/lbm)	2.3260×10^{0}	Kilojoule/Kilogram (kJ/kg)
Unit Angle	Degrees (^{o})	1.745329×10^{-2}	Radians (rad)

Acceleration of Gravity $= 32.1725\ ft/s^2$
$= 9.80621\ m/s^2$

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